Fermi GBM Observations of LIGO GW150914

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on behalf of the *Fermi* GBM Science Team

V. Connaughton, E. Burns, A. Goldstein, L. Blackburn et al.

(arXiv 1602.03920)

Fermi GBM Observations of LIGO Gravitational Wave Event GW150914

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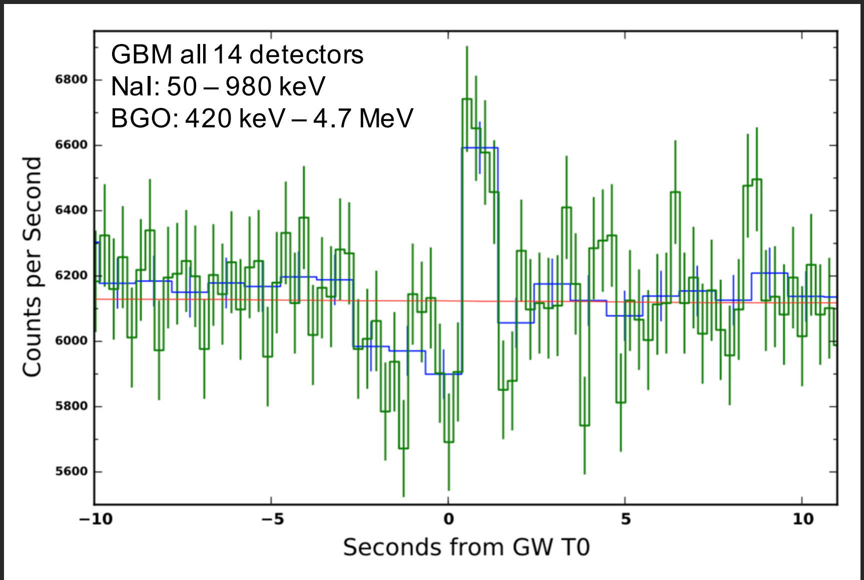
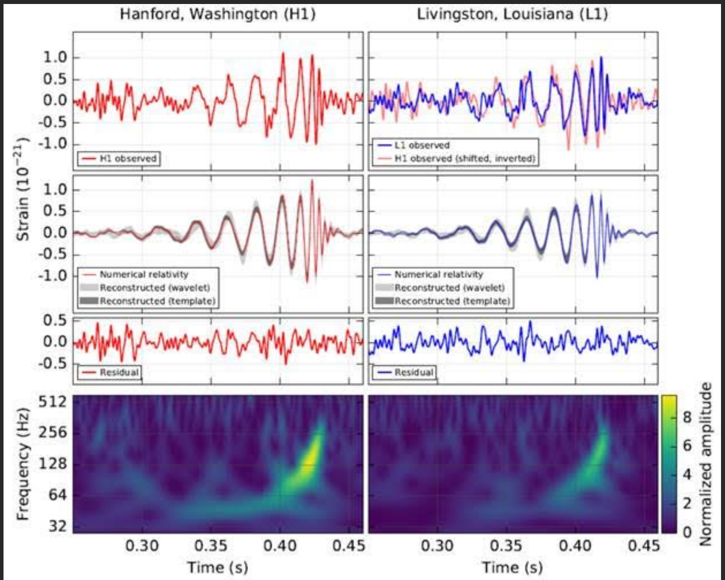
Did GBM detect an electromagnetic (EM) counterpart ?

GW150914-GBM

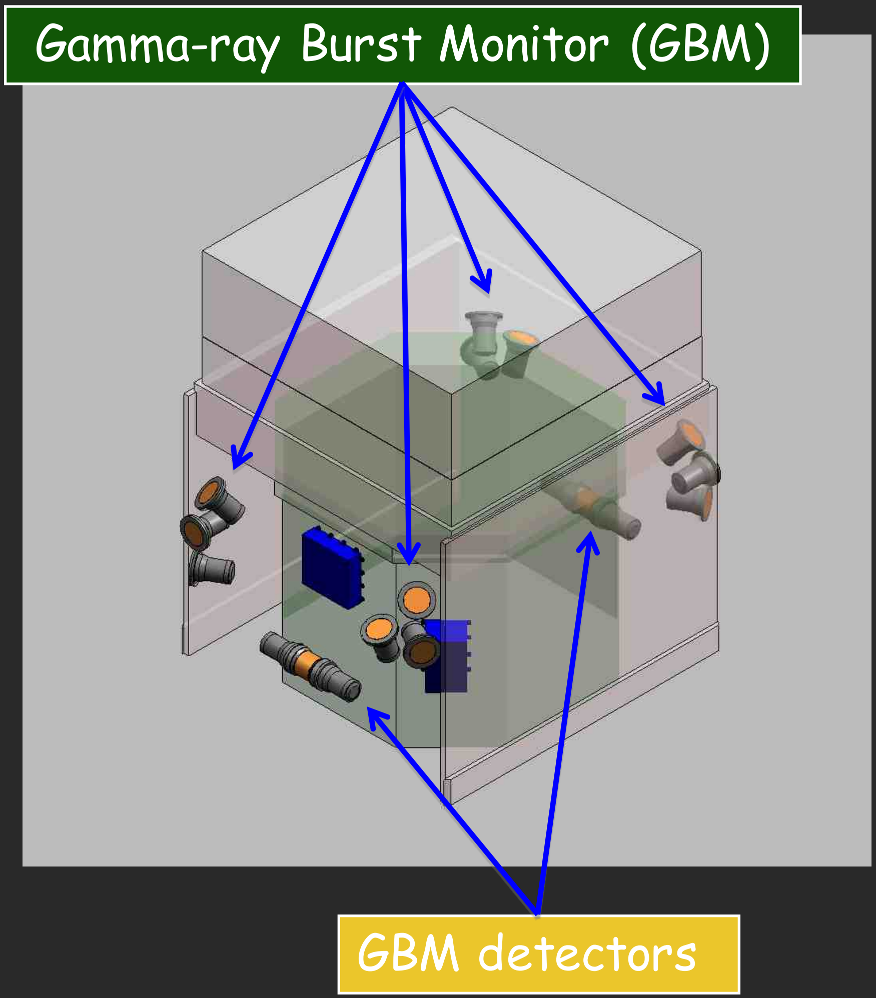


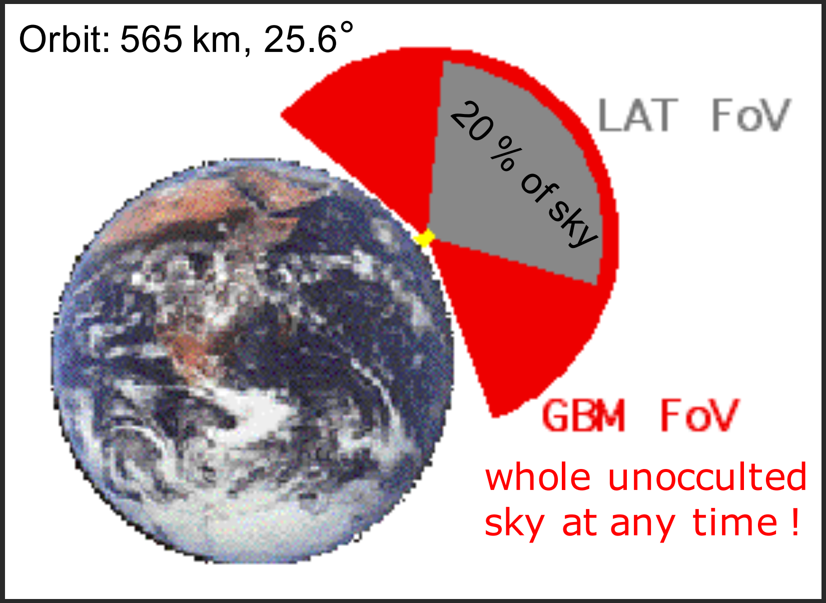
?

GW150914

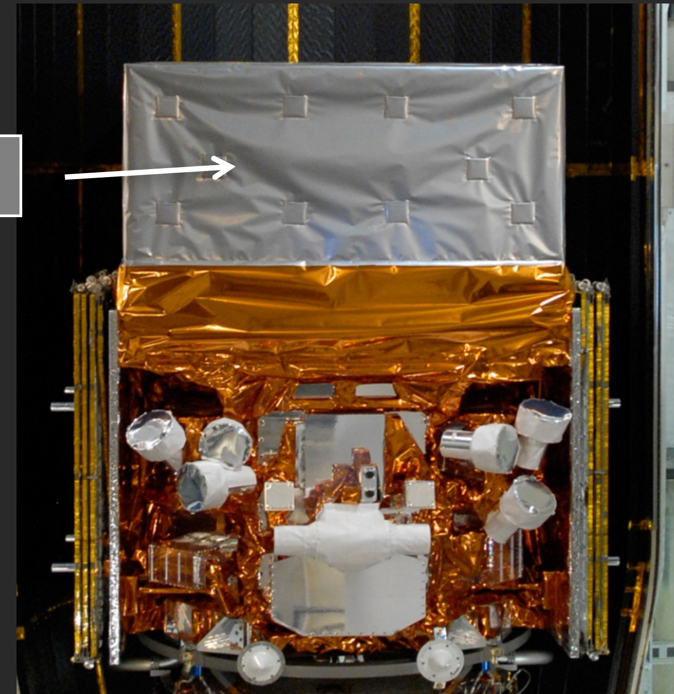


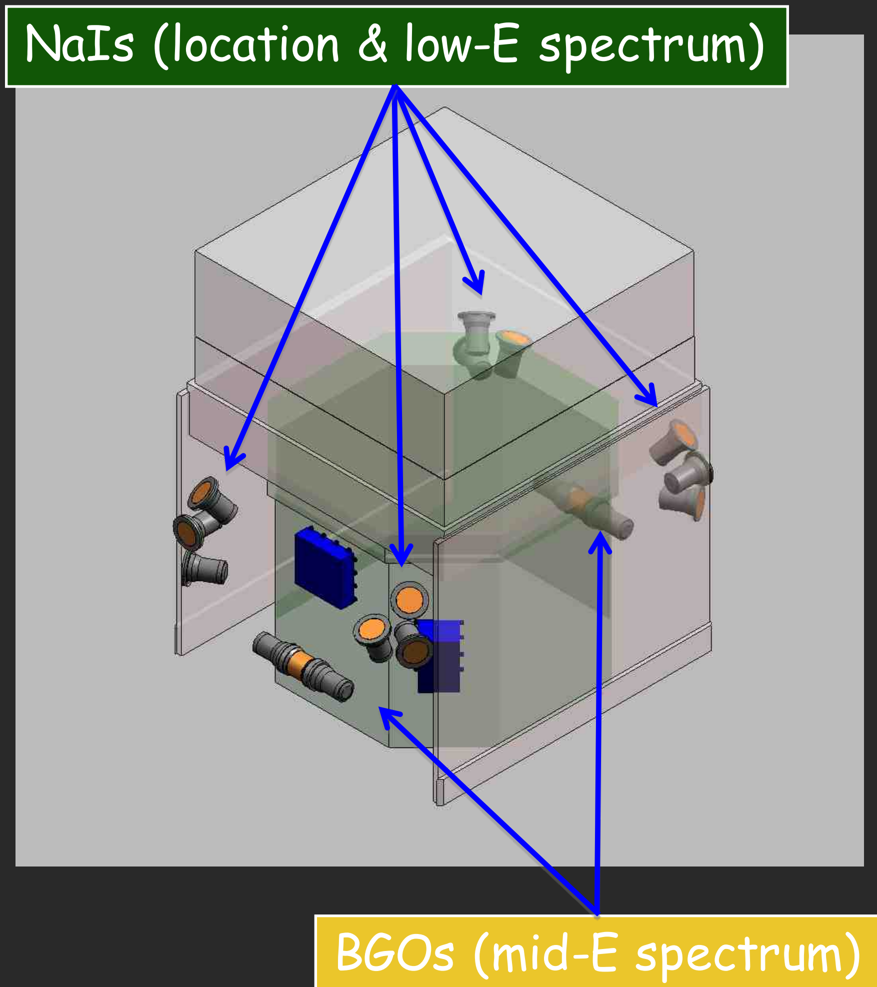
The *Fermi* Observatory

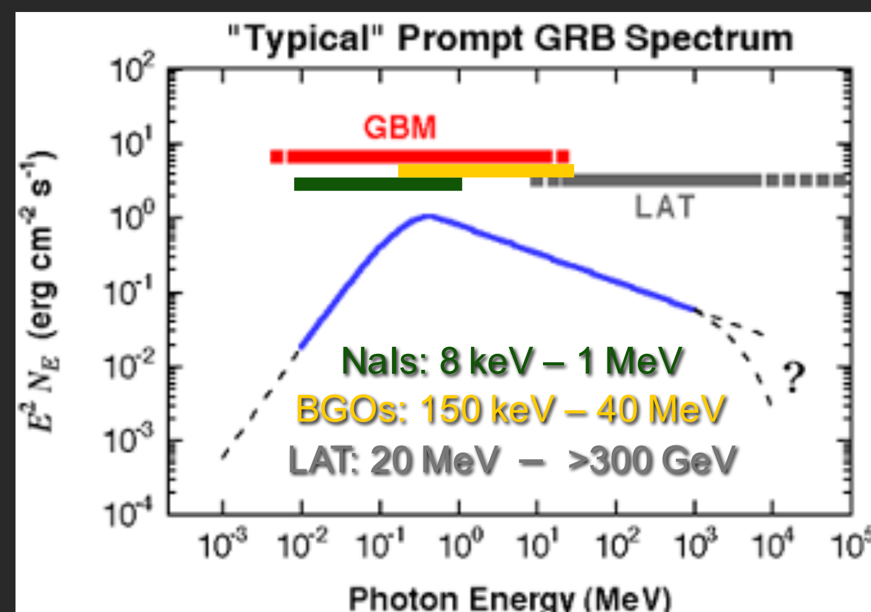




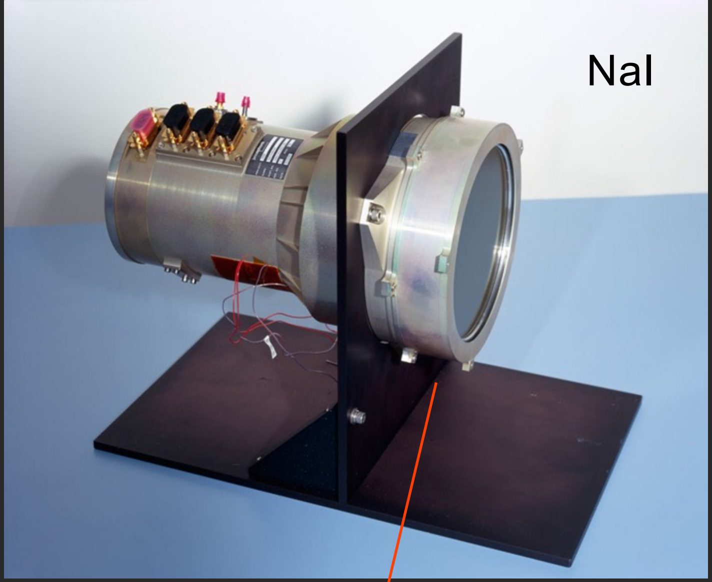
The *Fermi* Observatory

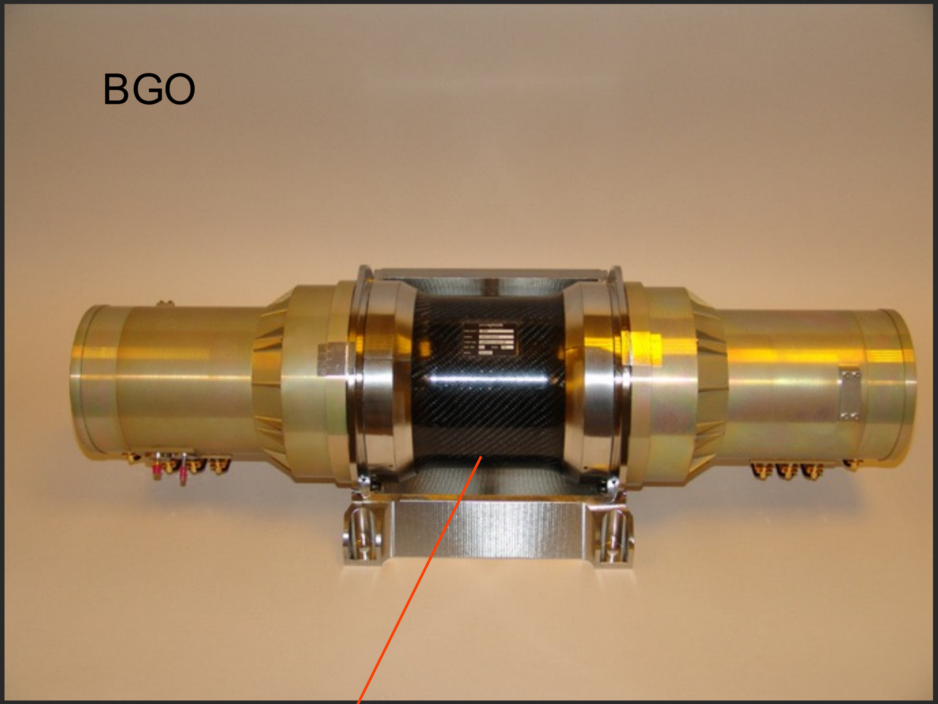


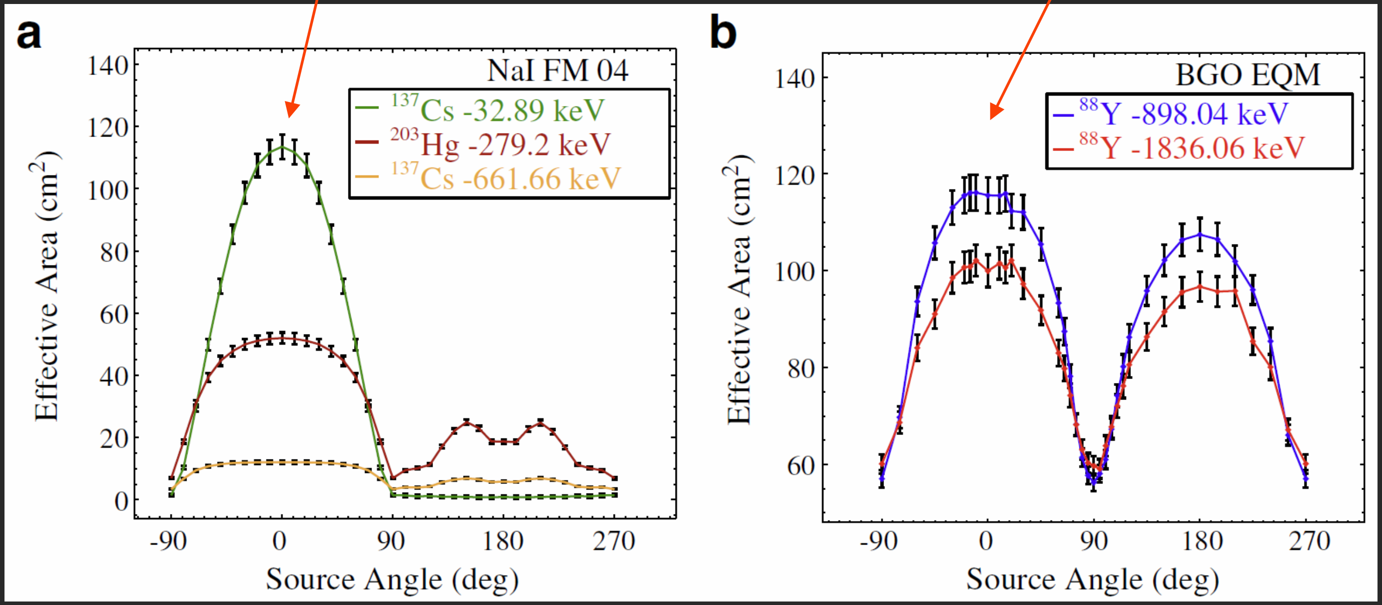




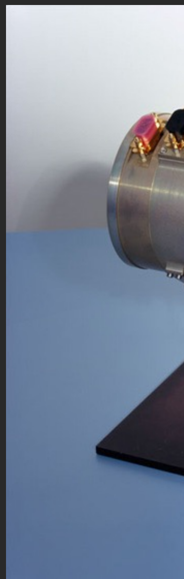
GBM Detectors

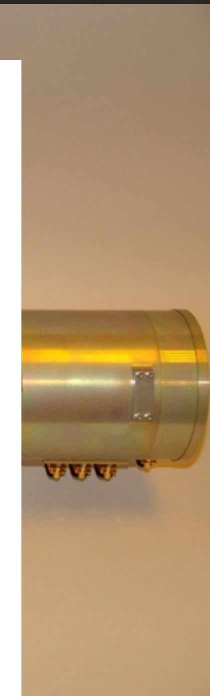


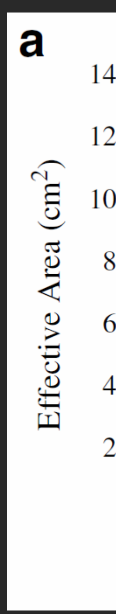


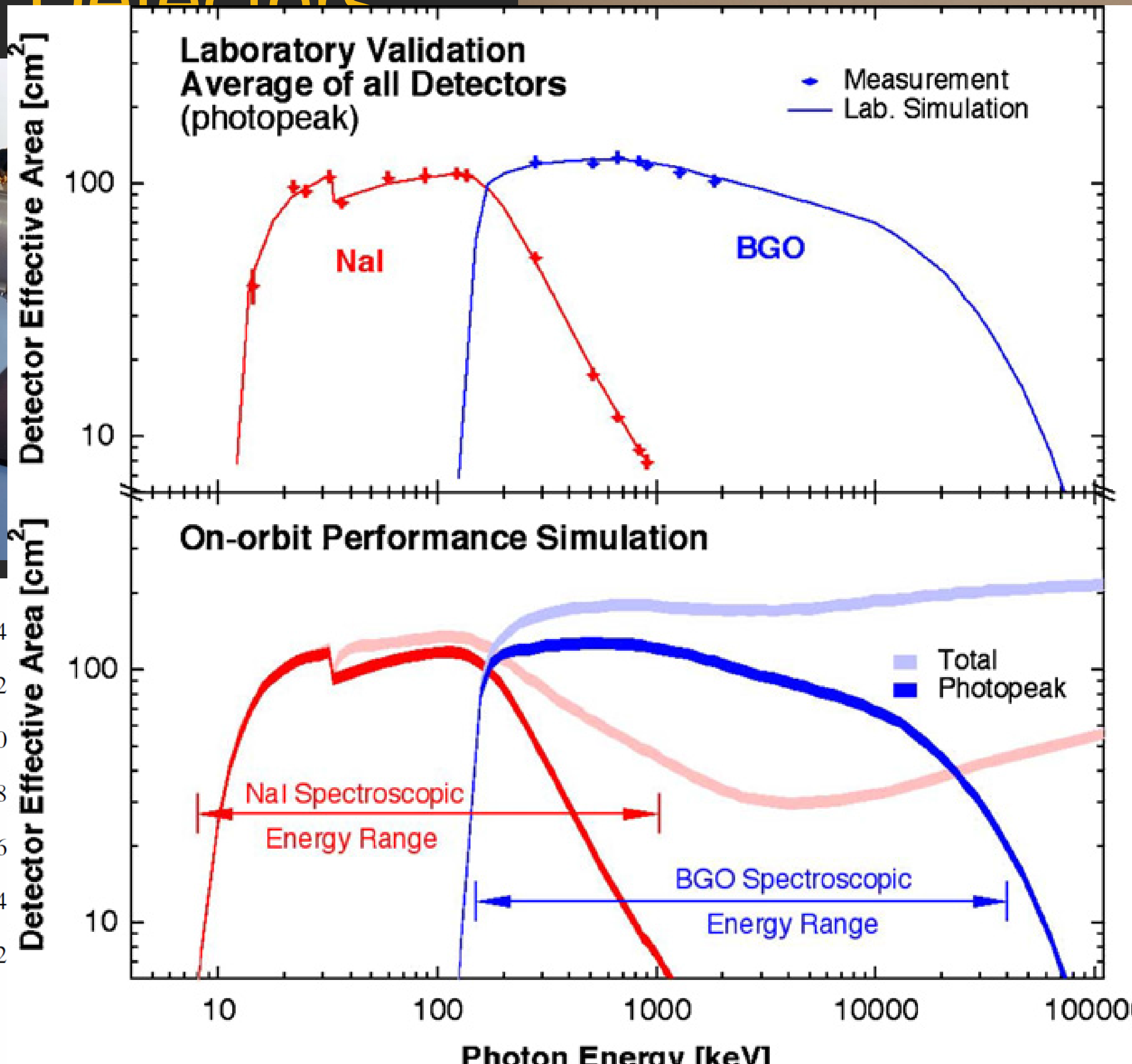


GBM Detectors

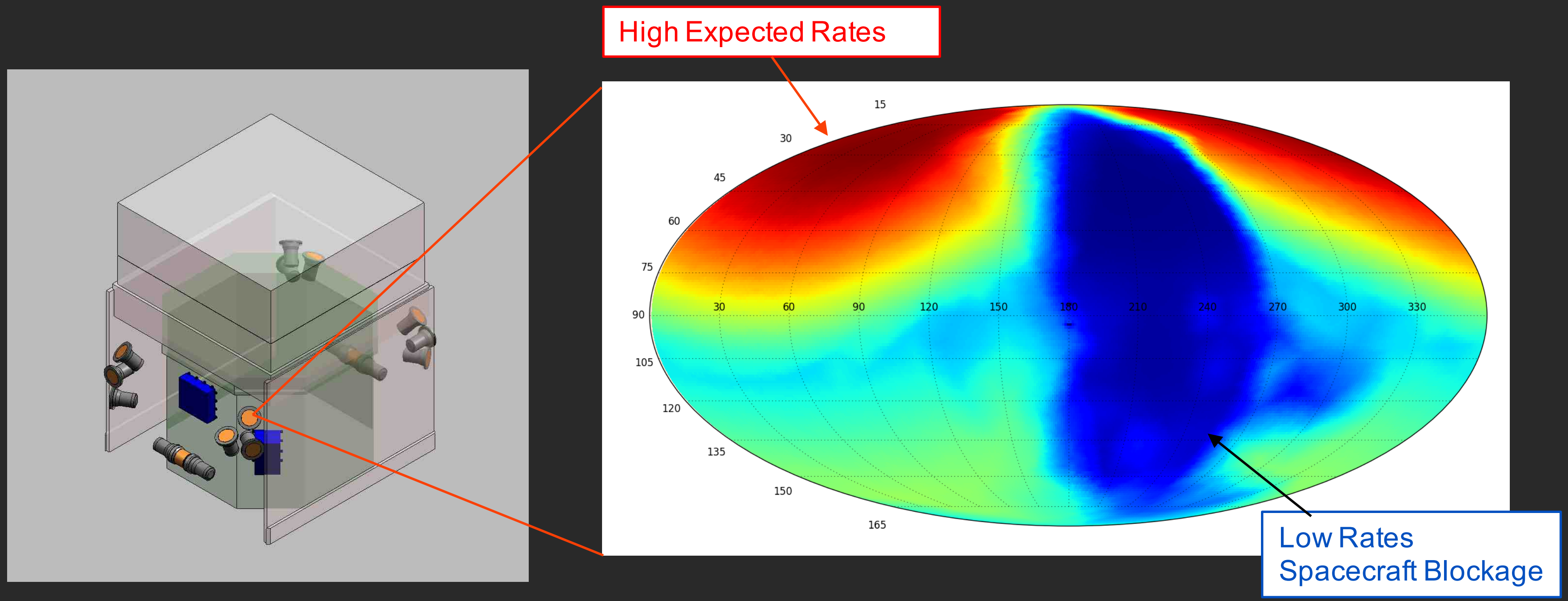






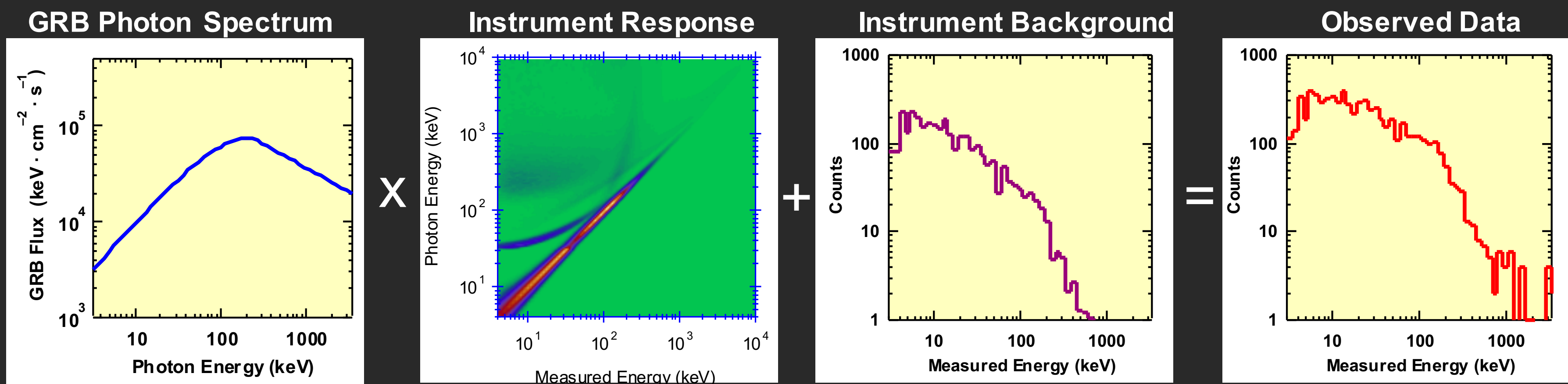


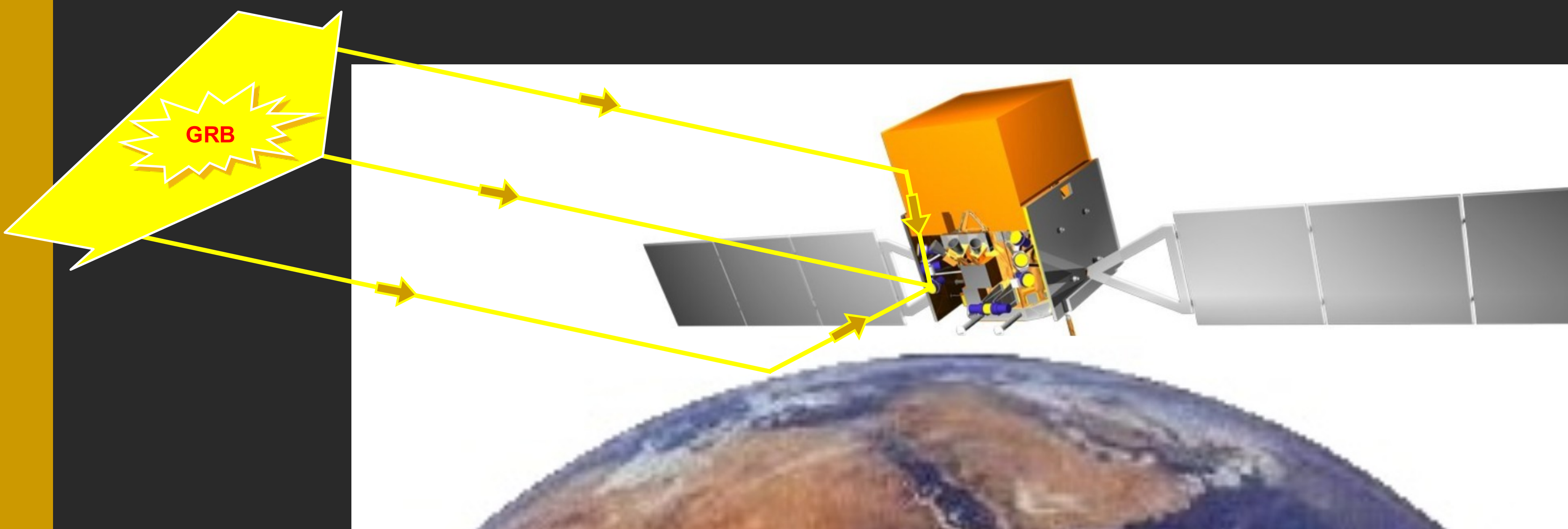
GBM Localization Method



- Localization is performed by comparing the relative observed rates from the GRB in each detector to the expected rates on a 1 degree grid
- This requires an assumption of the spectrum, and the sky grid limits to a statistical minimum uncertainty of 1 degree radius

GBM Detector / Instrument Response





GBM Data

Data Type	Time Resolution	Energy Resolution
TRIGDAT	1024/256/64 ms	8 channels
CTIME	256/64 ms	8 channels
CSPEC	4096/1024 ms	128 channels
TTE	2 μs	128 channels
CTTE (New!)	2 μs	8 channels

- TRIGDAT: used primarily for localization & quick look
- CTIME: temporal analysis
- CPSEC: spectral analysis
- Initially TTE was available ~30s pre-trigger - ~300 s post-trigger
- Continuous TTE (CTTE) implemented on November 26, 2012

GBM On-Board Triggering

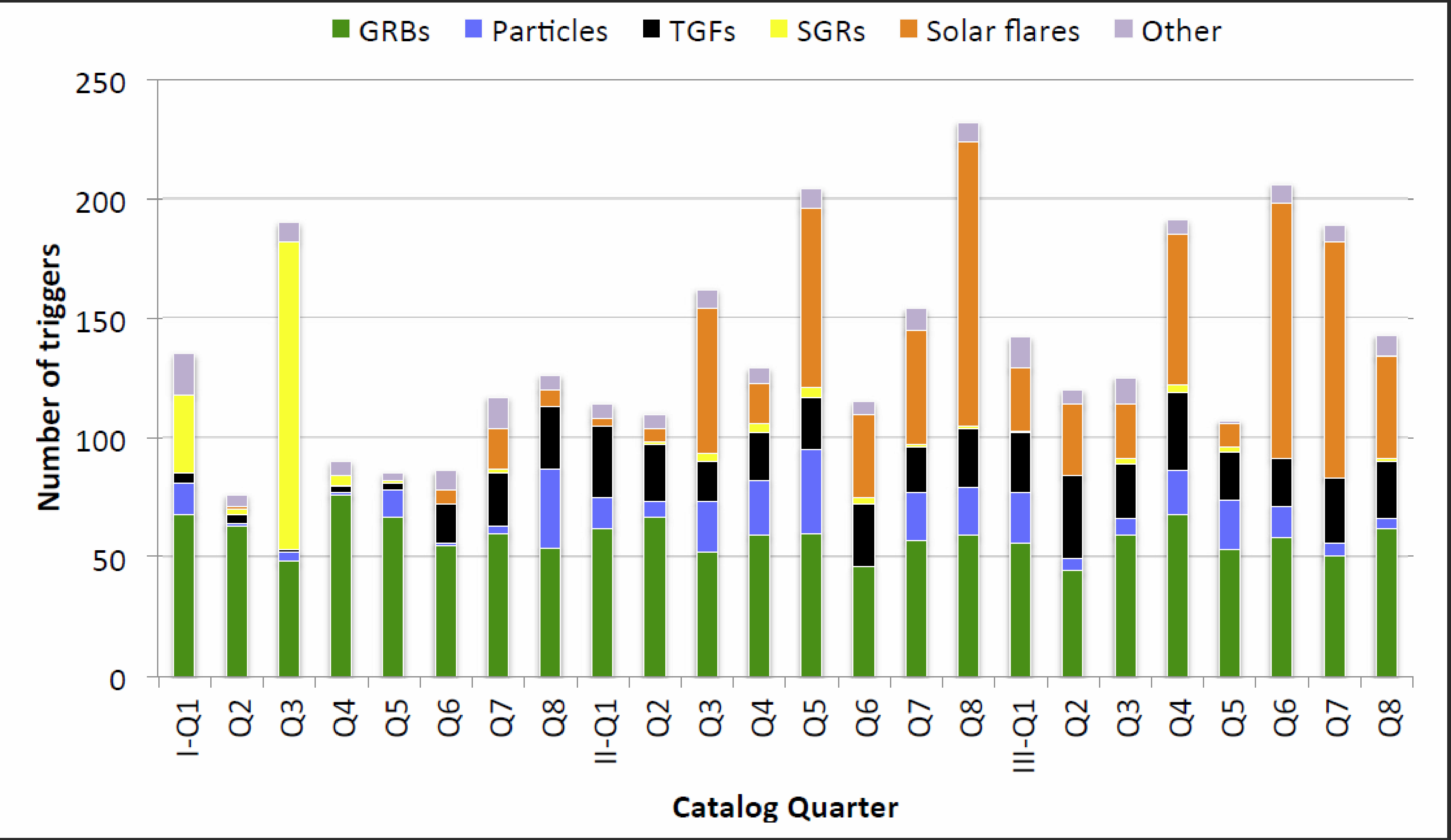
- GBM triggers when 2 or more detectors exceed background by n sigma over t timescale in e energy band.

- 70 algorithms operating simultaneously.
  - $4.5 \leq n \leq 7.5$
  - $16\ \text{ms} \leq t \leq 8.096\ \text{s}$
  - e = one of 25 - 50 keV, 50 - 300 keV, 100 - 300 keV, > 300 keV

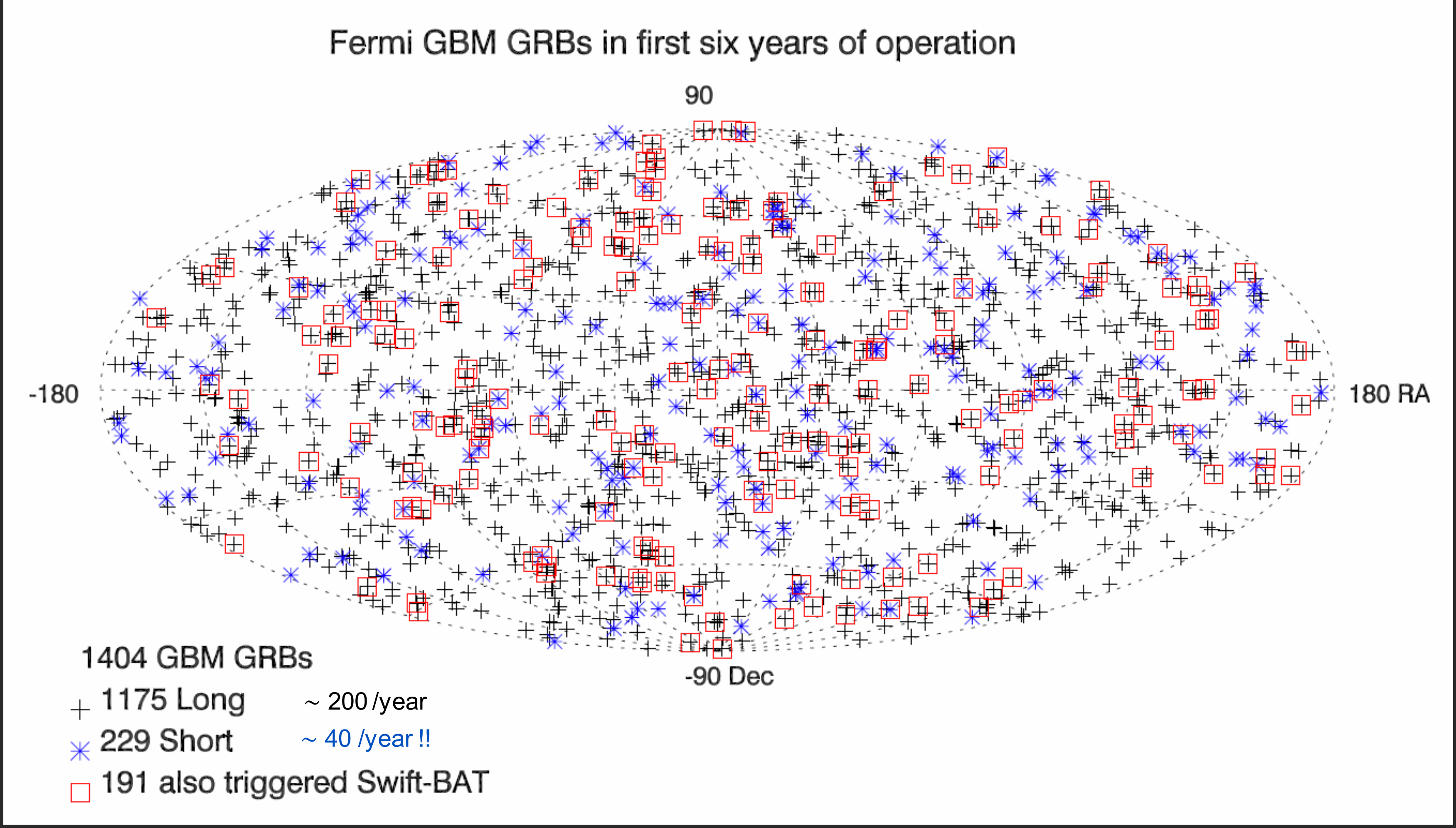
⇨ What does GBM trigger on?

What does GBM see?

Lots of stuff

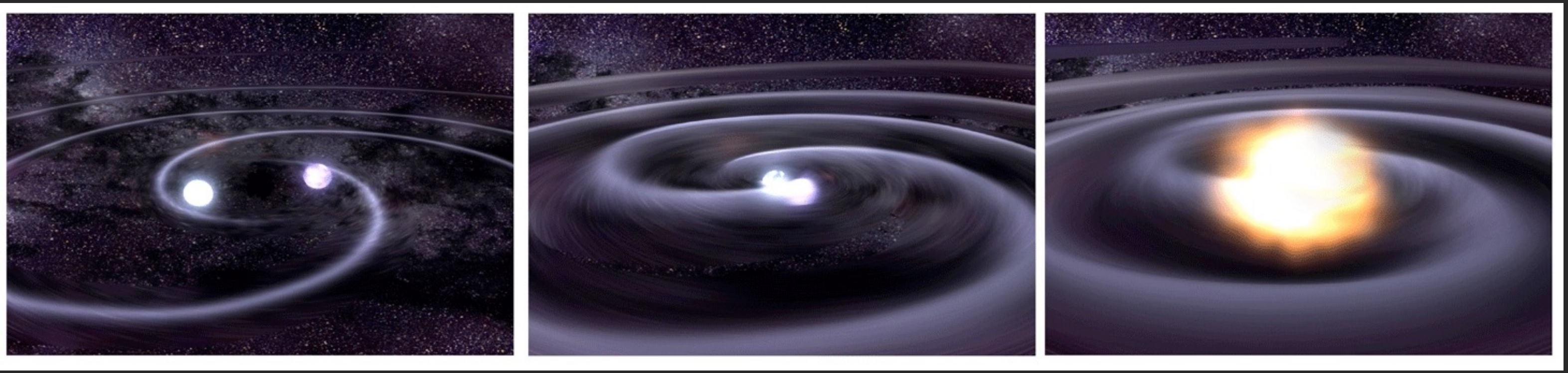


Fermi GBM in first six years of operation

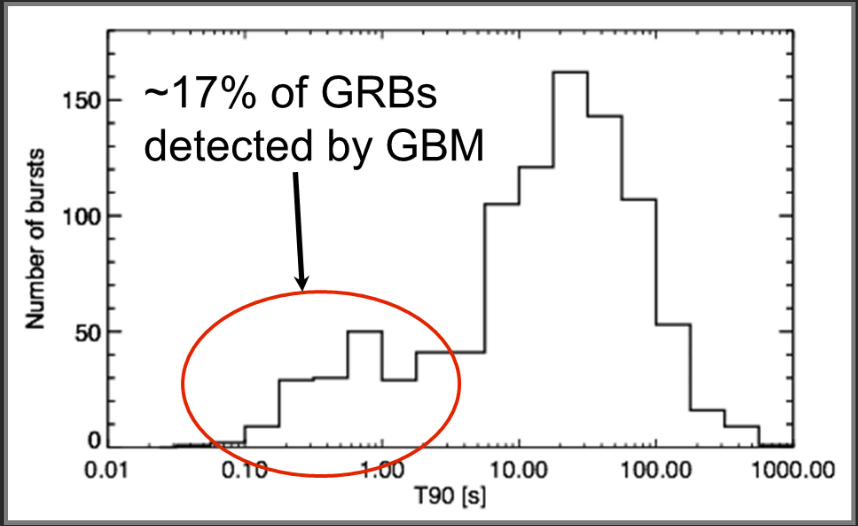


GBM detected Short GRBs

- GBM instrument best suited for EM counterpart search of GW events!



Short GRBs → NS-NS, NS-BH
GBM: ~ 40 triggered short GRBs/year
Swift: ~ 9 short GRBs/year



GBM offline searches

- Dedicated search algorithms for un-triggered transient sources
  - Magnetar burst (~200), thousands of Terrestrial Gamma-ray Flashes (TGFs) and hundreds of other Galactic sources
  - Short GRBs
    - Additional ~ 35 per year, most of them unverified by other instruments (needs verification)
    - Initially developed for Terrestrial Gamma-ray Flash (TGF) search
    - Using CTTE data, 2μs time resolution, 128 energy channels
    - 2 detectors: 2.5 σ and another 1.25 σ above background
    - 10 timescales — 0.1s to 2.8s
    - 5 energy ranges (optimized on GBM-triggered weak sGRBs)
    - Unfavorable geometry of the two above-threshold detectors are eliminated
    - Soft and long duration candidates are removed
  - Targeted search of GBM data for short GRBs

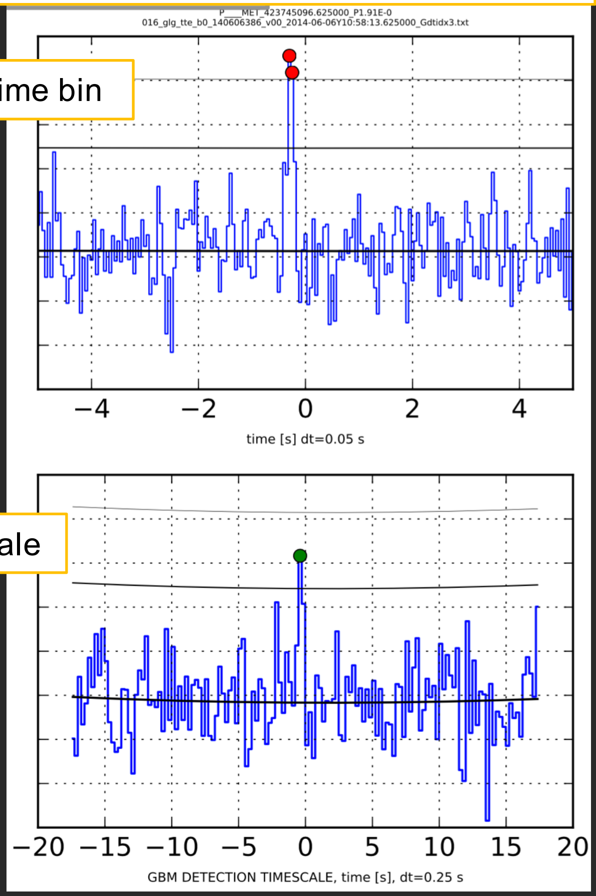
GBM Un-triggered Short GRB Candidate

2014-06-06 10:58:13.625
Found in 0.25s time binning
93 - 494 keV energy range

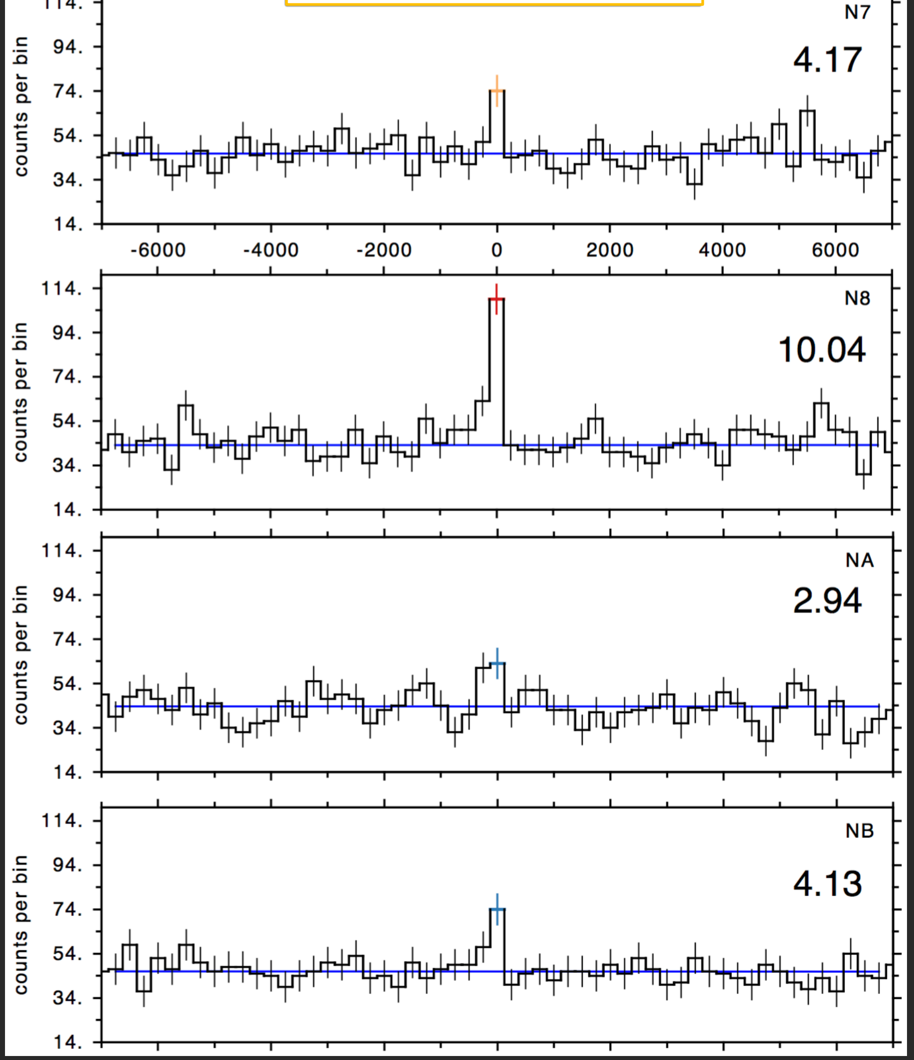
INTEGRAL Anti-Coincidence Shield (ACS) lightcurve

ACS native time bin

GBM timescale



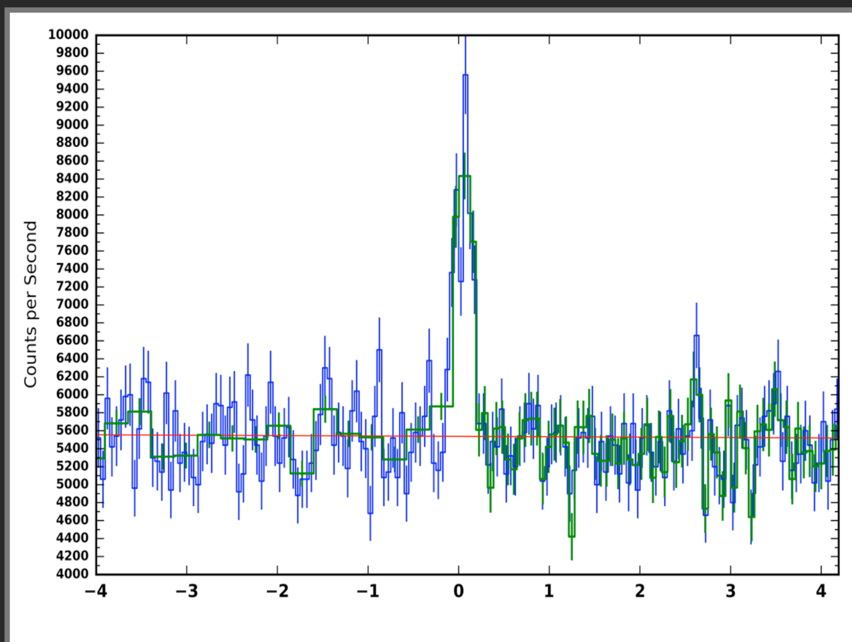
SWIFT GRB 140606A



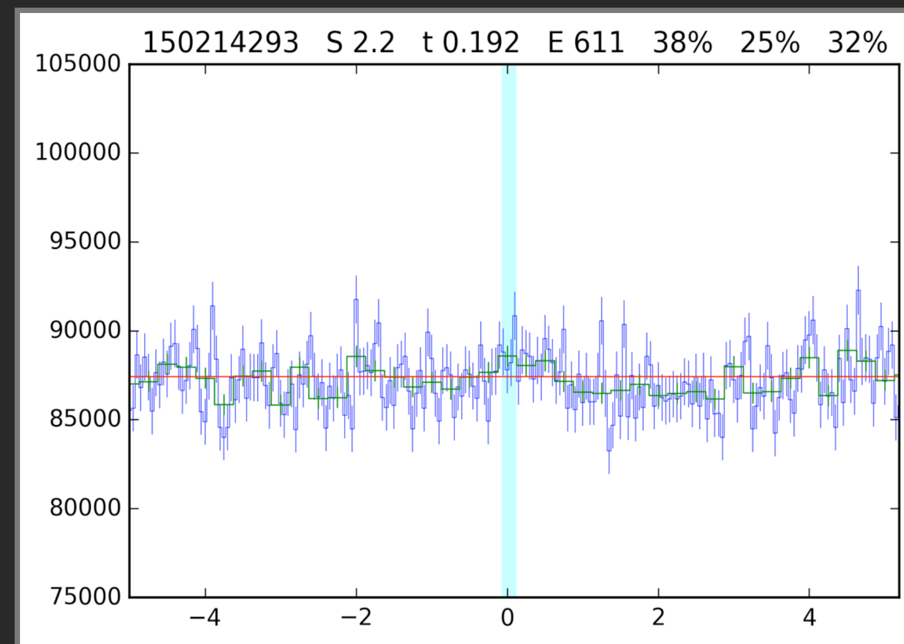
INTEGRAL SPI/ACS

- GBM GRB 150214293

GBM



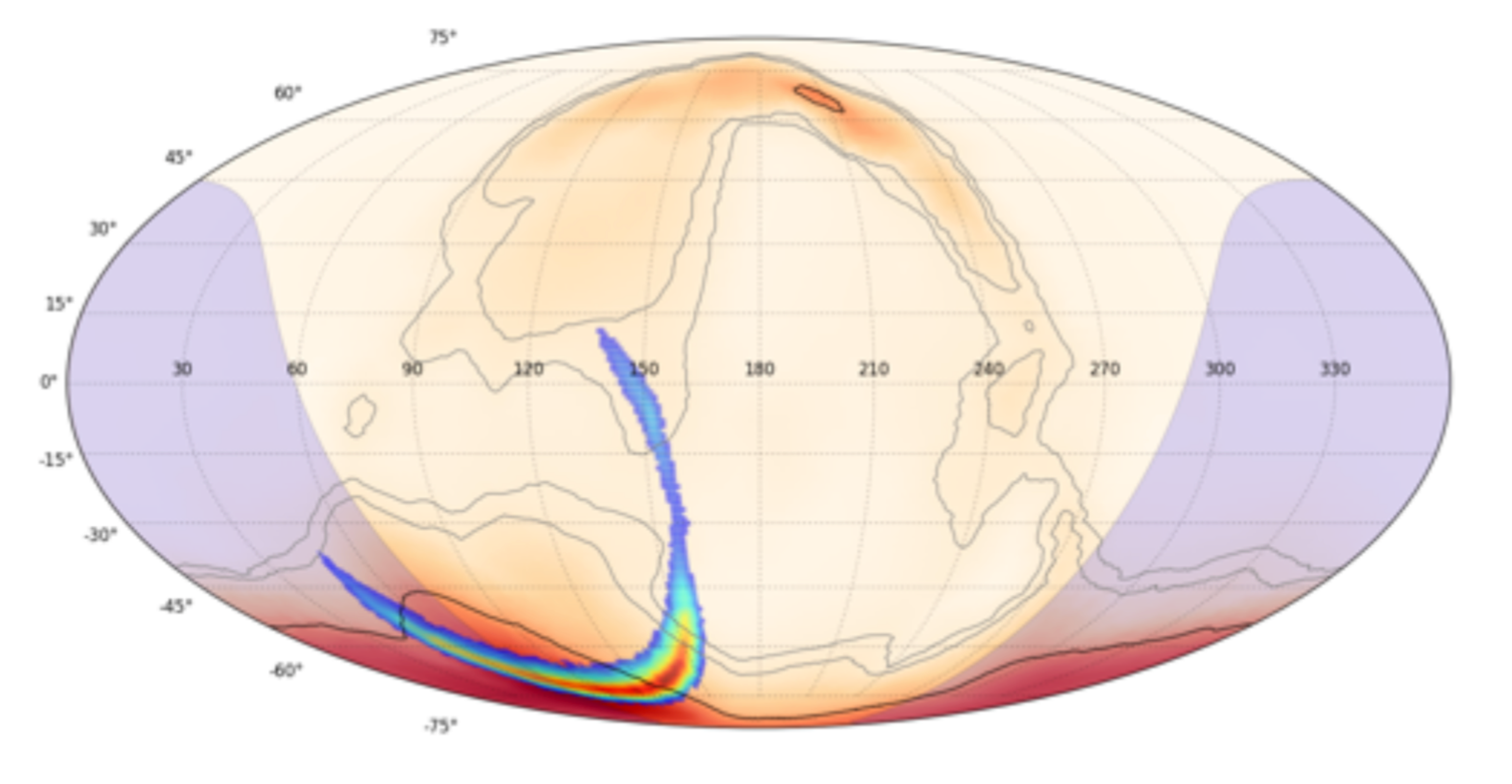
SPI/ACS



- GBM and SPI-ACS teams are working together to better understand the systematics between the two instruments

The Curious Case of GW150914-GBM

- Weak signal that is temporally coincident with GW150914, and other properties of the GBM event indicates that it could be a short GRB
- GBM localization area is large, but consistent with LIGO, and potentially reduces sky area for follow-up observers by 2/3



The Curious Case of GW150914-GBM

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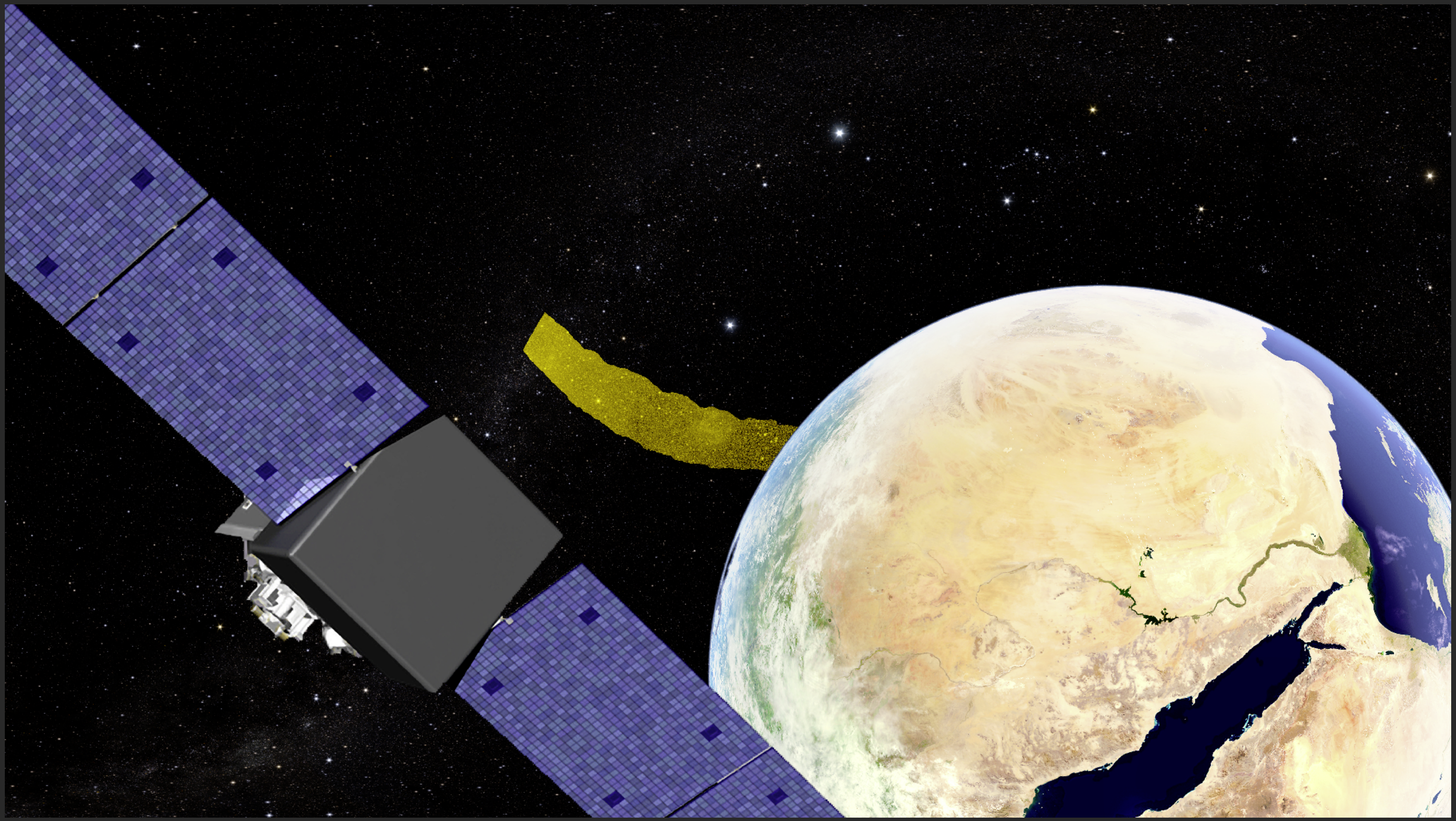
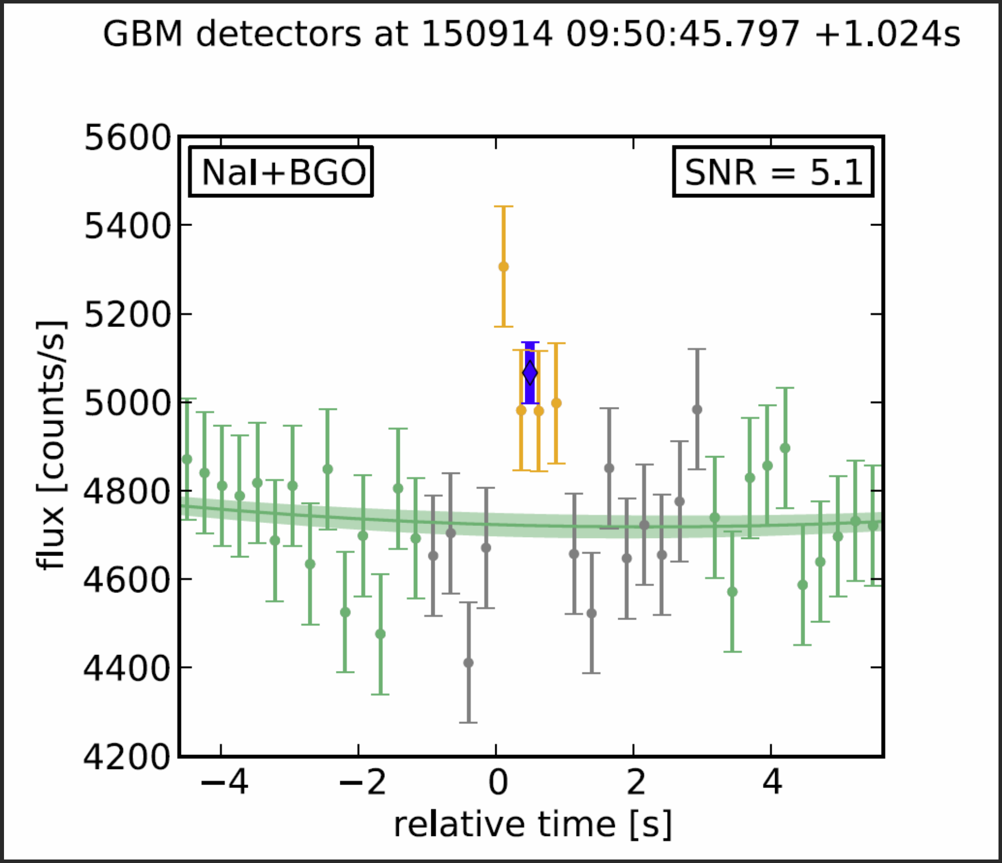


GW150914-GBM

- GW150914-GBM identified by Lindy Blackburn's targeted search
  - False Alarm Rate = 1.2 x 10^{-4} Hz

Model-dependent count rates

The raw count rates are weighted and summed to maximize signal-to-noise for a modeled source



Targeted Search of GBM data

- Identify EM counterparts in the GBM data to any candidate GW events
  - Developed during LIGO S6 observing run (Blackburn et al. 2015)
- Coherent search over all GBM detectors (NaI and BGO)
  - seeded with time & (optionally) sky location of any LIGO/Virgo candidate event.
  - using the full response for a point source at each sky position
  - over user-specified time window
  - estimate of background rate by polynomial to local date outside the foreground interval
- For each template spectrum (soft, medium & hard) and sky location
  - detector counts for each energy channel are weighted according to the modeled rate
  - and inverse noise variance due to background.
  - The weighted counts from all NaI and BGO detectors are summed to obtain a signal-to-noise optimized light curve for that model.
  - Each model is also assigned a likelihood by the targeted search based on the foreground counts
- Will reveal short-duration candidates between 0.256 s to 8.192 s (CTIME)
- Candidates are ranked by a Bayesian likelihood statistic

GBM GCN Circular

TITLE: GCN CIRCULAR
NUMBER: 18339
SUBJECT: LIGO/Virgo G184098: Fermi-GBM ground-based follow-up
DATE: 15/09/20 01:46:08 GMT
FROM: Lindy Blackburn at CfA <lindy.blackburn@ligo.org>

Lindy Blackburn (CfA), Michael S. Briggs (UAH), Eric Burns (UAH), Jordan Camp (NASA/GSFC), Nelson Christensen (Carleton College), Valerie Connaughton (USRA), Adam Goldstein (NASA/MSFC), Tyson Littenberg (UAH), John Veitch (Birmingham), Judith Racusin (NASA/GSFC), Peter Shawhan (UMD), Leo Singer (NASA/GSFC), Binbin Zhang (UAH)

We report on a sub-threshold targeted followup of LIGO candidate event G184098 in Fermi-GBM survey data for bursts between 0.256s and 8s in duration, and covering a range of GRB spectral models. Although there was no on-board GBM trigger at the time of the event, Fermi-GBM was exposed to a large fraction of the LIGO sky position and thus we searched offline data for untriggered events. The GBM FOV is blocked by the Earth which occults 67 degrees from (RA, DEC) = (355.14, -21.23). Thus GBM observation is able to cover about 87.8% of the cWB sky posterior, and 91.5% of the LIB posterior. We scanned several minutes of GBM live-time centered on the GW event time using a pipeline developed specifically for following-up LIGO-Virgo events in GBM archival data during the LIGO-Virgo S6/VSR3 run [1].

The search identified a possible transient beginning at 150914 09:50:45.8, about 0.4s after the reported LIGO burst trigger time of 09:50:45.39, and it lasted for about 1 second. The intrinsic time resolution for this search was 0.256s. Of the three GRB model spectra tested in the search, the event was best matched to the one corresponding to the hardest spectrum. Using GBM

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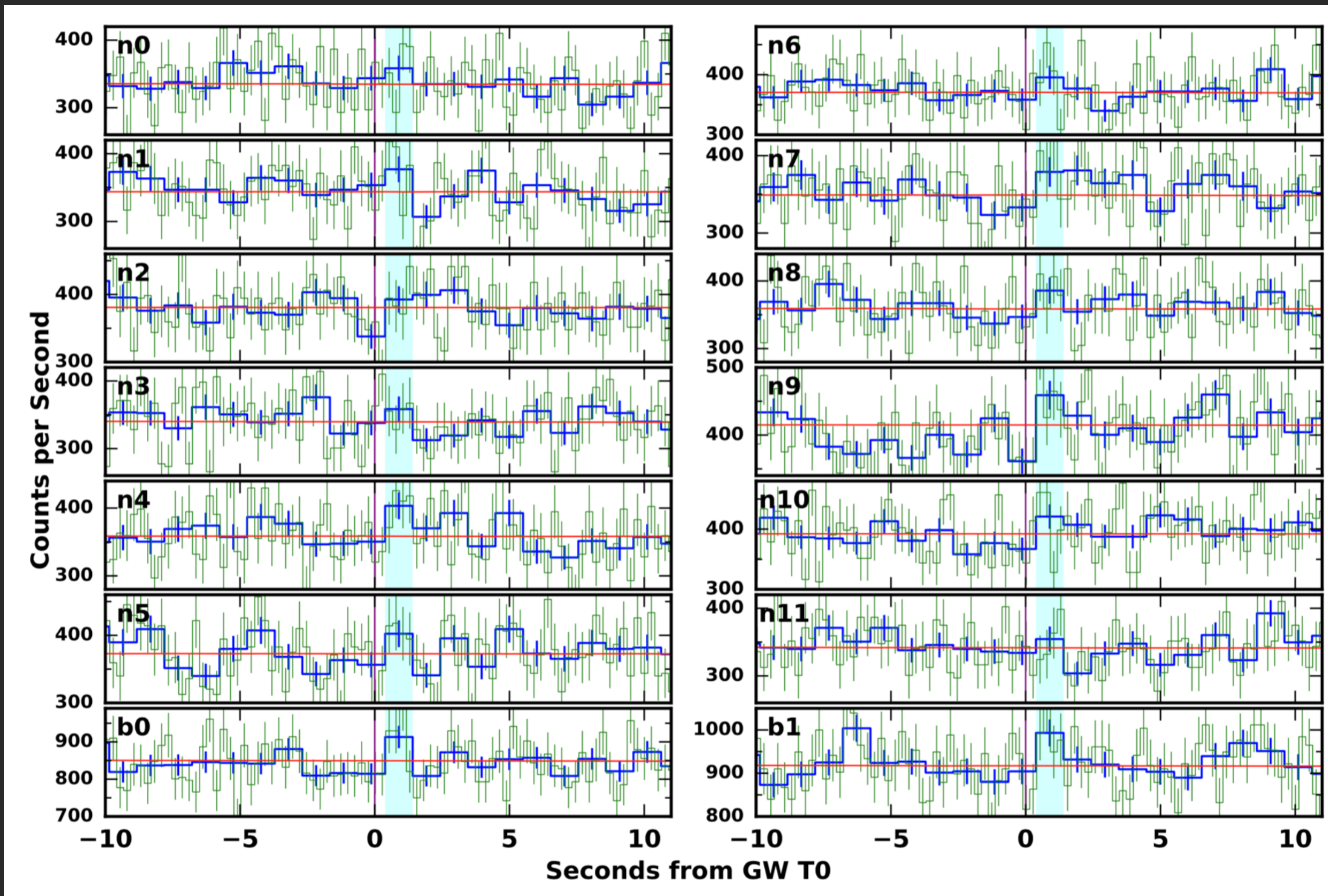
GW150914-GBM

- Detector data

NaI 0	NaI 1	NaI 2	NaI 3	NaI 4	NaI 5
1.31	1.81	0.64	1.05	2.42	1.68
NaI 6	NaI 7	NaI 8	NaI 9	NaI 10	NaI 11
1.31	1.64	1.45	2.20	1.61	0.66
BGO 0	BGO 1				
2.25	2.56				

σ deviation from a background fit

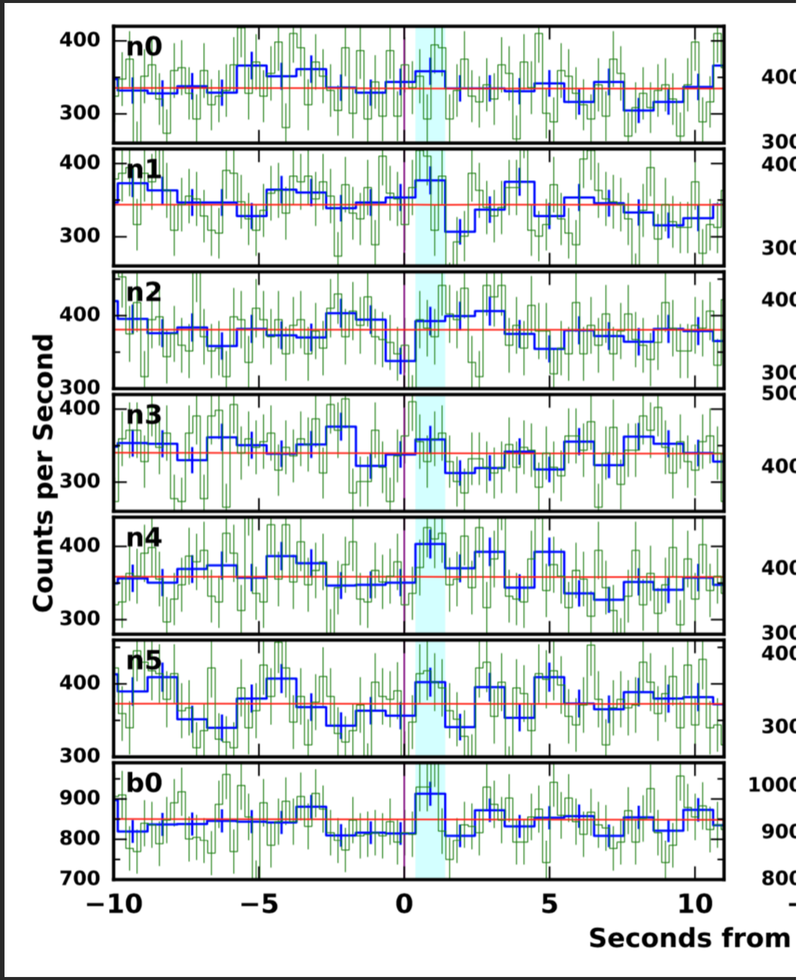


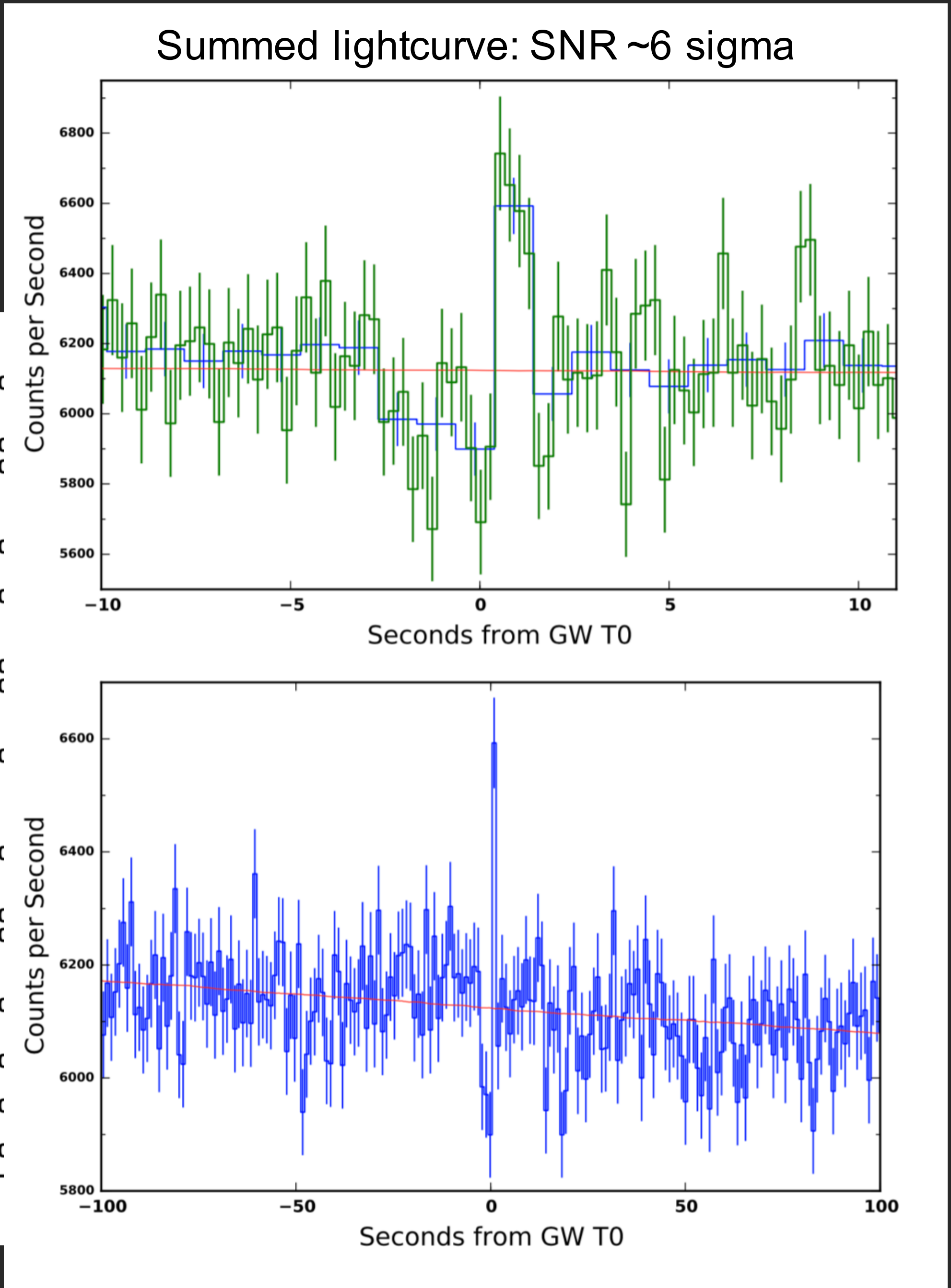
NaIs:
50 – 980 keV

BGOs:
420 keV – 4.7 MeV

GW150914-GBM

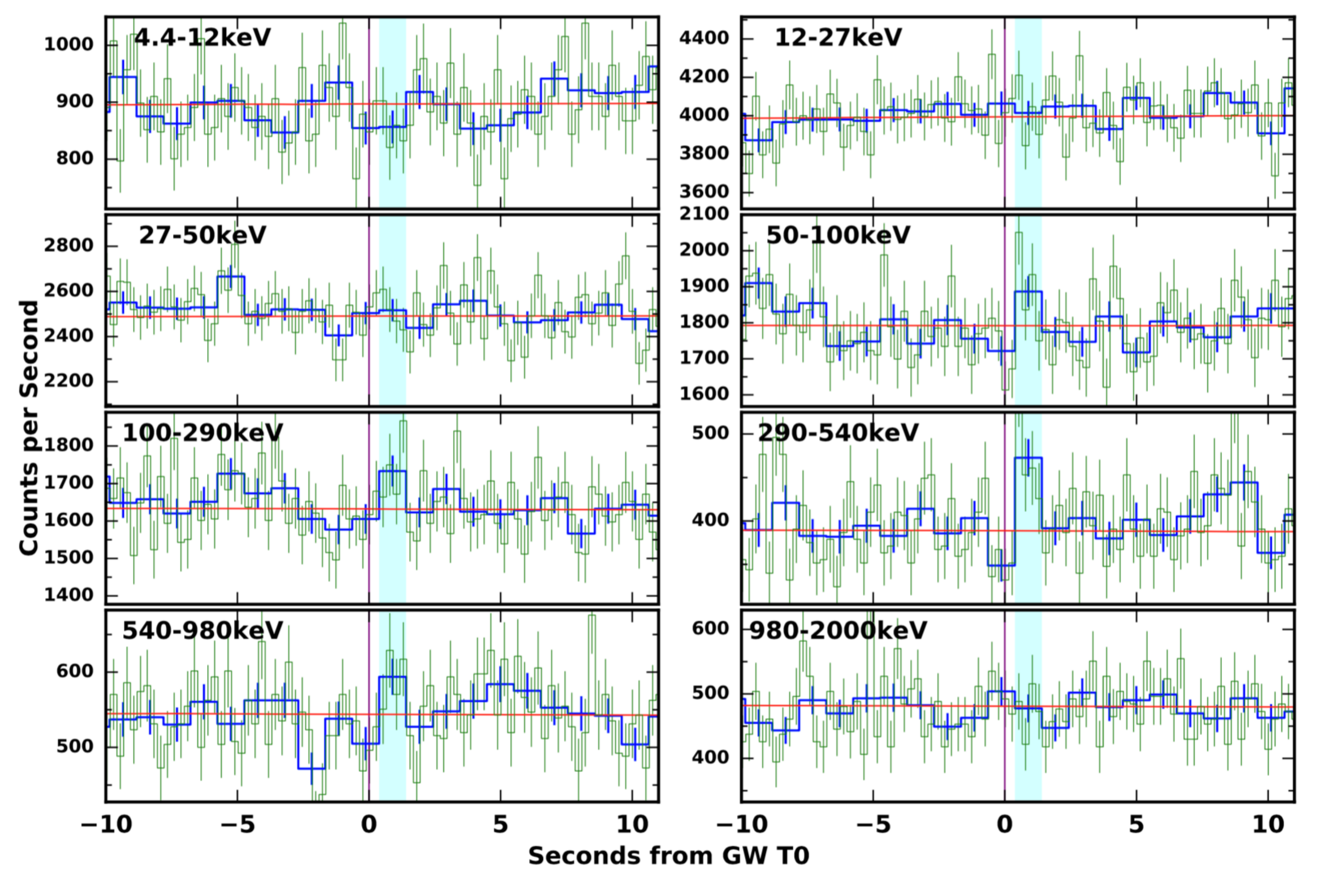
- Detector data





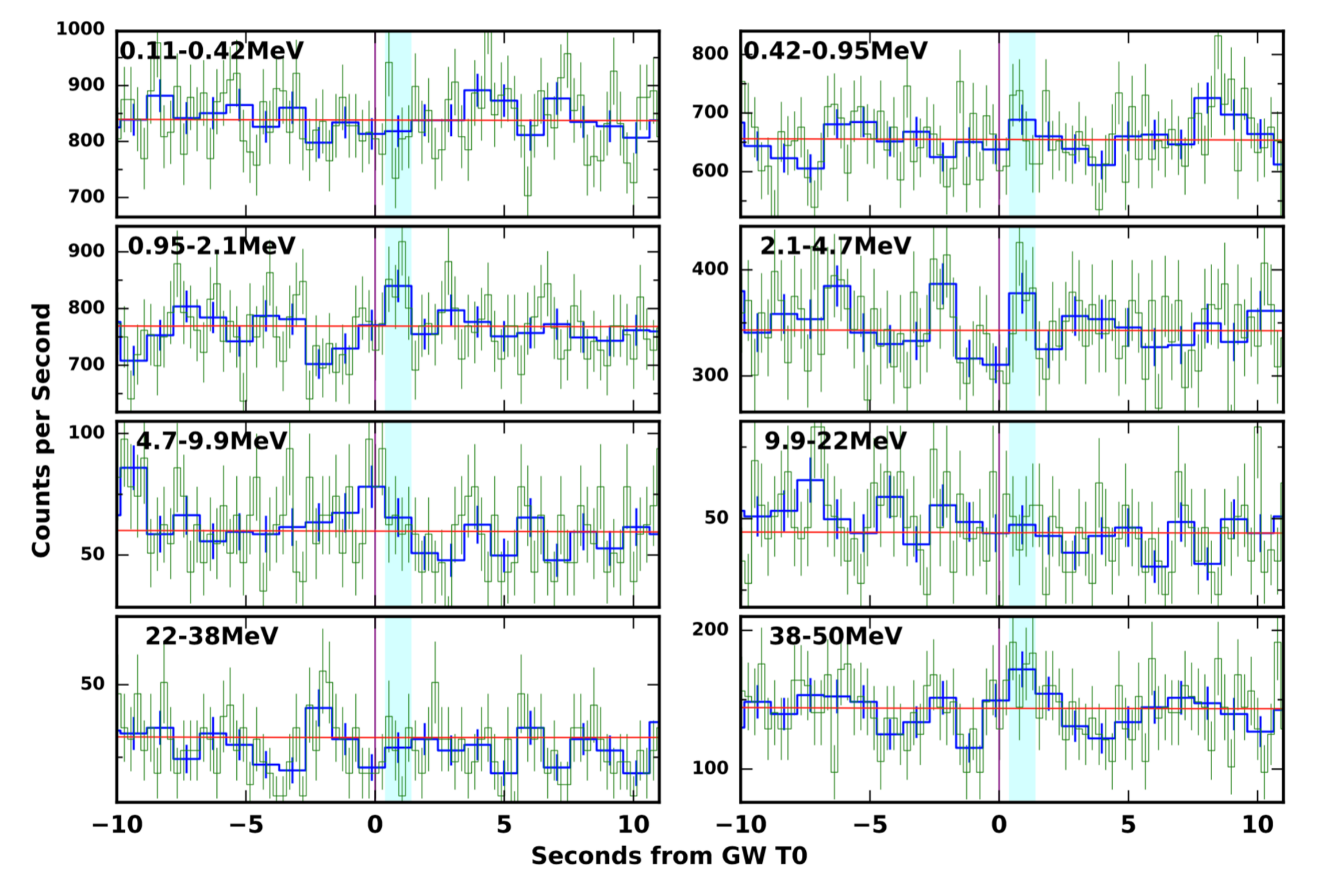
GW150914-GBM

- Count rates summed over NaI detectors in 8 energy channels

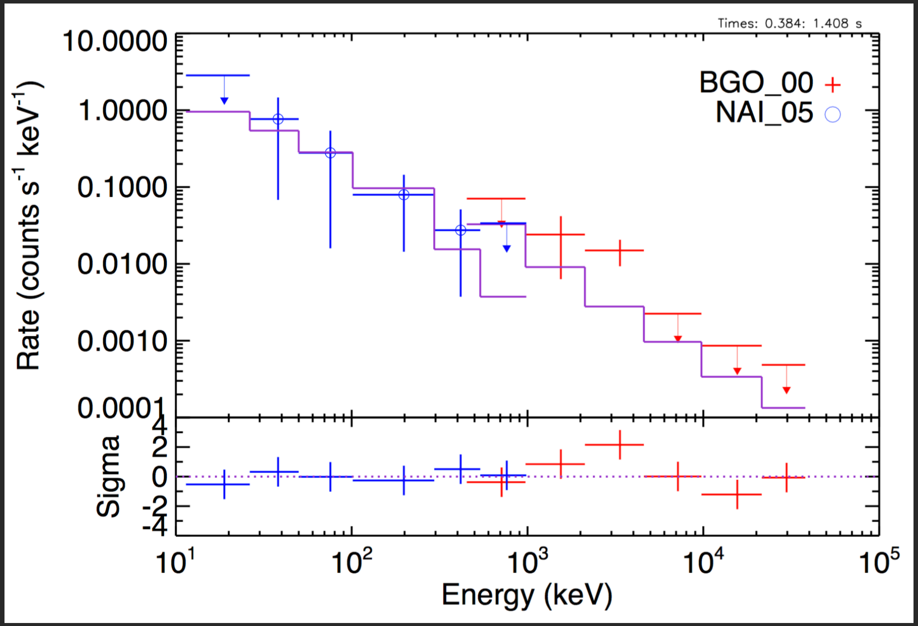


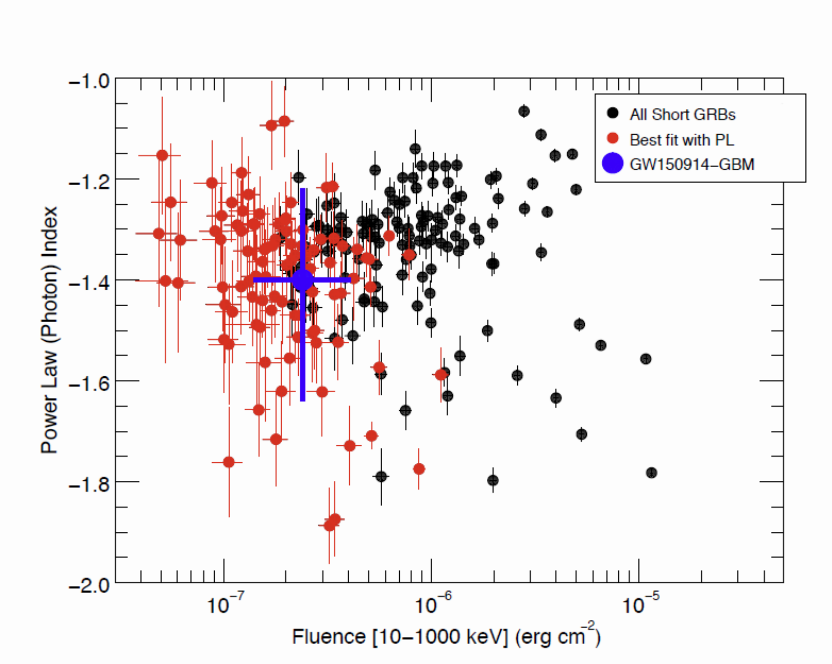
GW150914-GBM

- Count rates summed over BGO detectors in 8 energy channels



Energy spectrum of GW150914-GBM





best fit PL

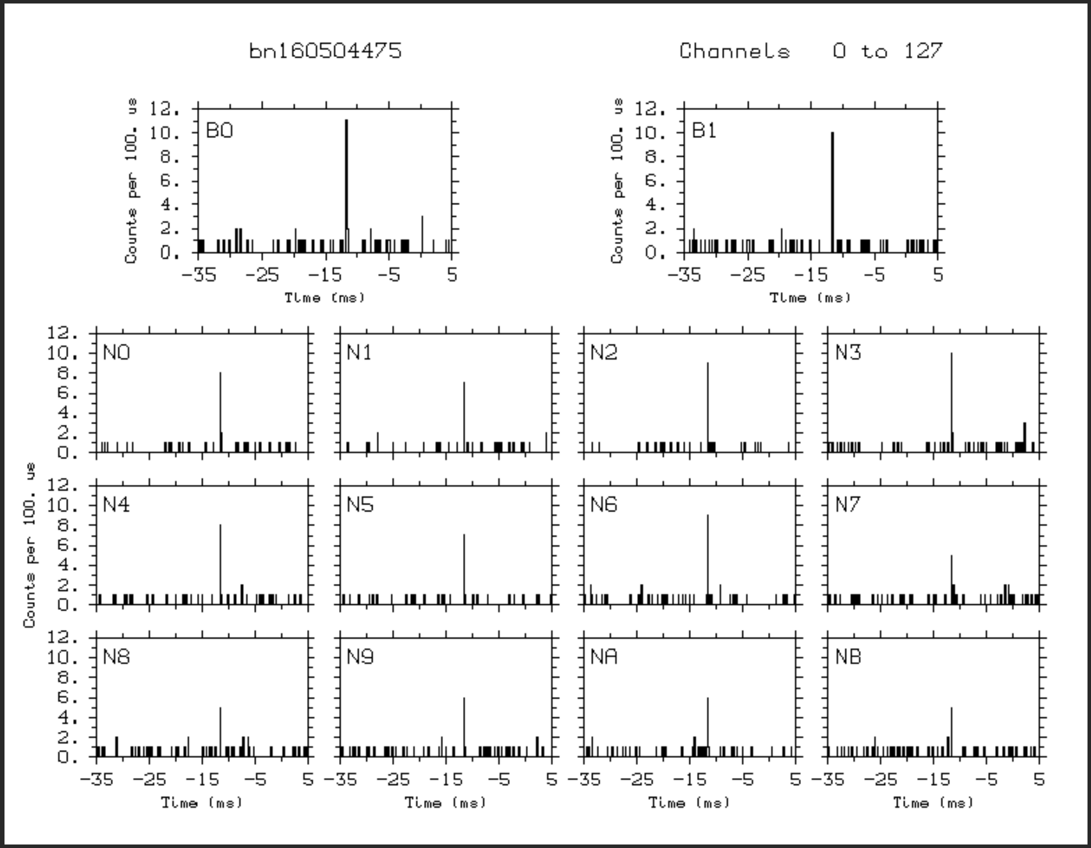
- index: $-1.40^{+0.18}_{-0.24}$
- amplitude: $0.002^{+0.002}_{-0.001}$ photons s^{-1} cm^{-2} keV^{-1}
- 10 – 1000 keV fluence: $2.4^{+1.7}_{-1.0} \times 10^{-7}$ erg cm^{-2}

Lightning Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs)			?			

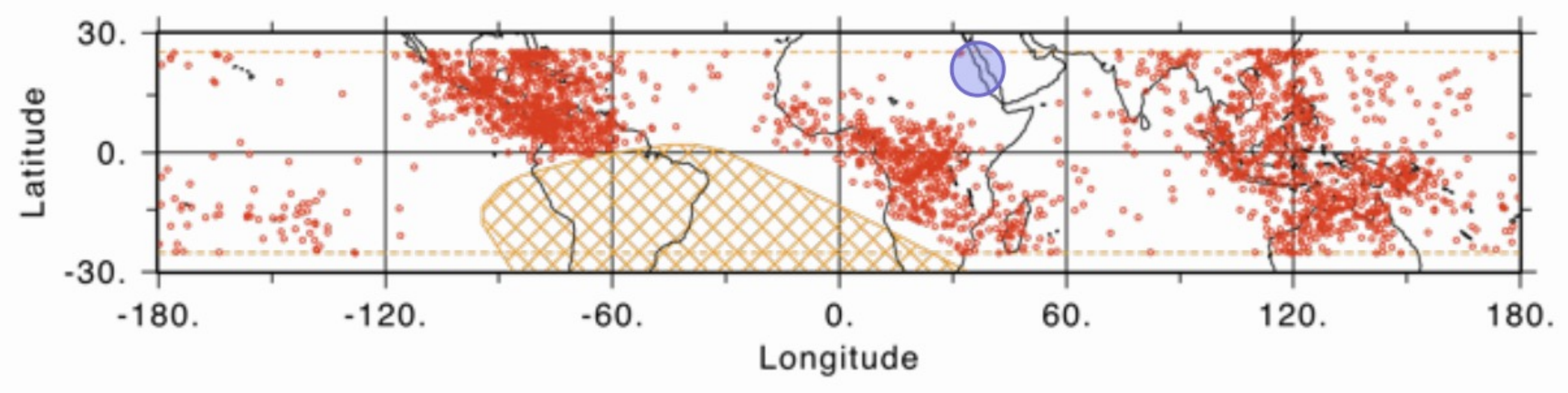
Lightning Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs)	No		?	No		



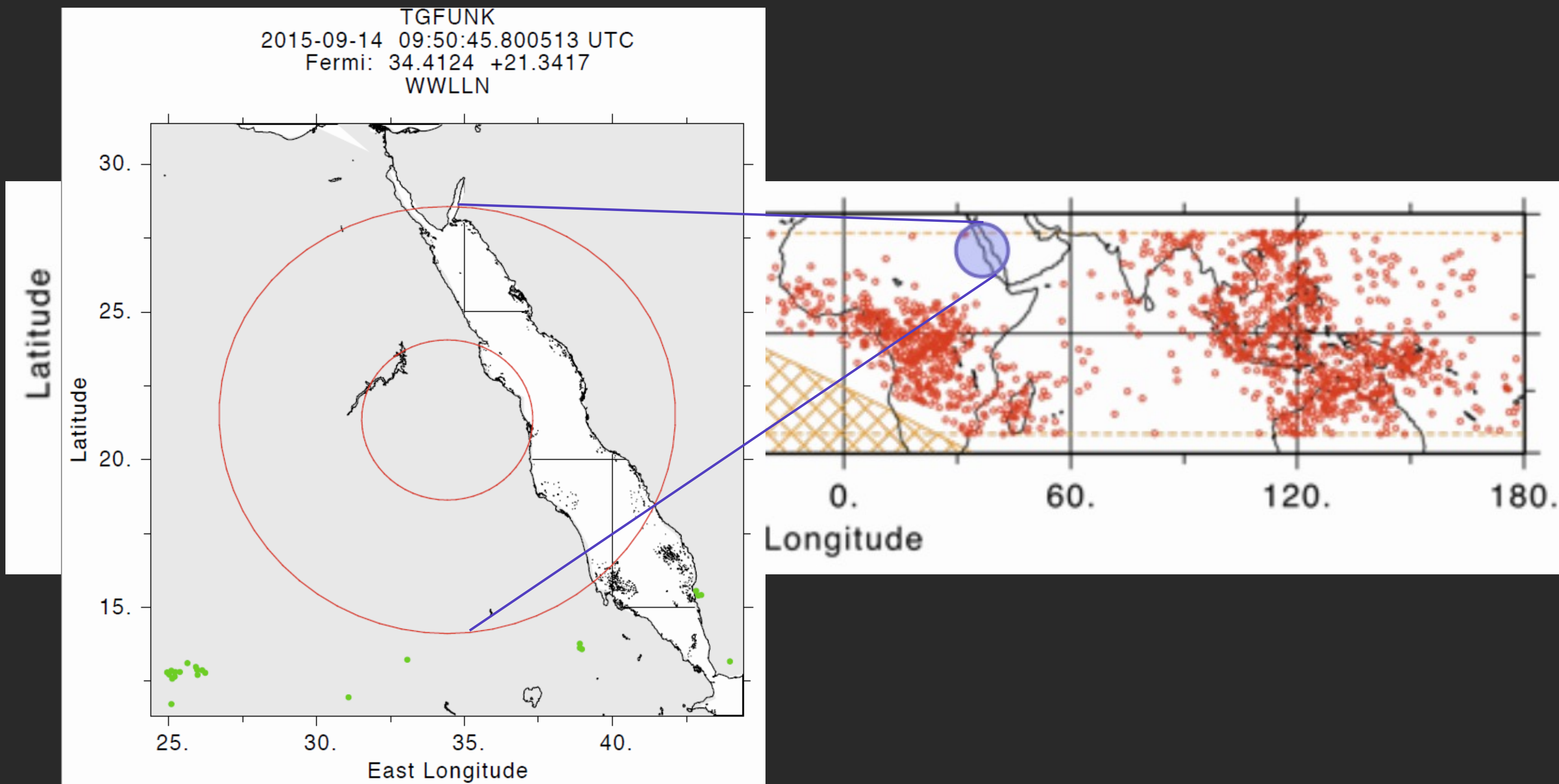
Lightning Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs)	No		**?**	No	No	



Lightning Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs)	No	No	?	No	No	No

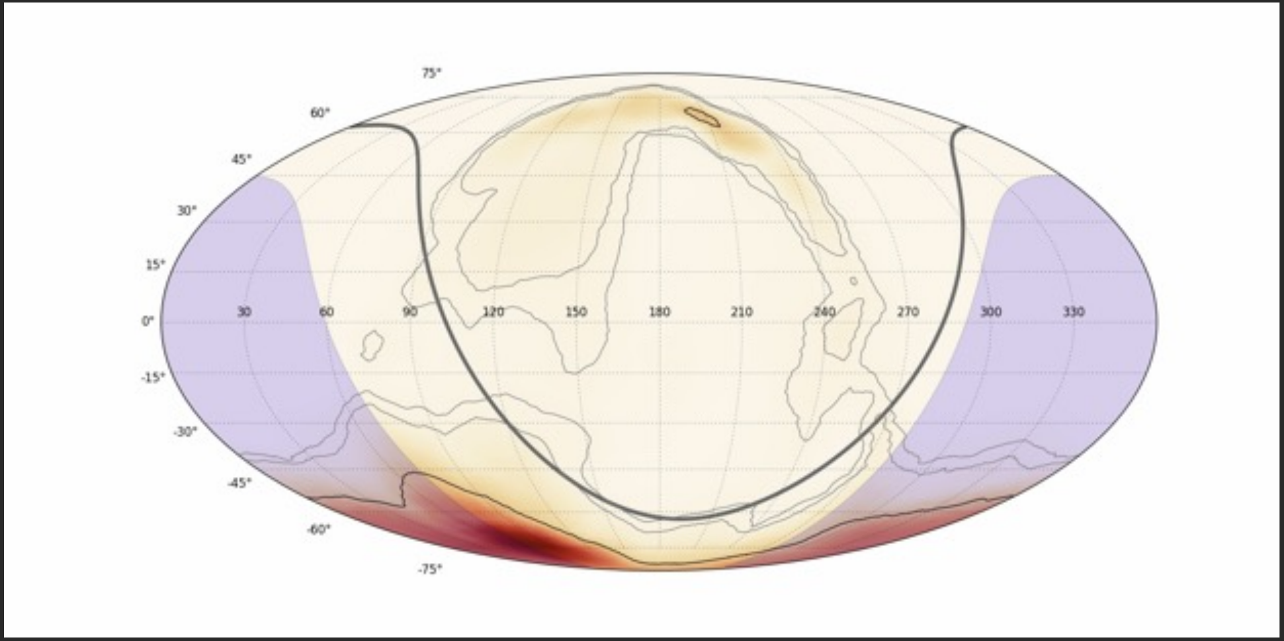


Galactic Source Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Galactic Sources					**N/A**	

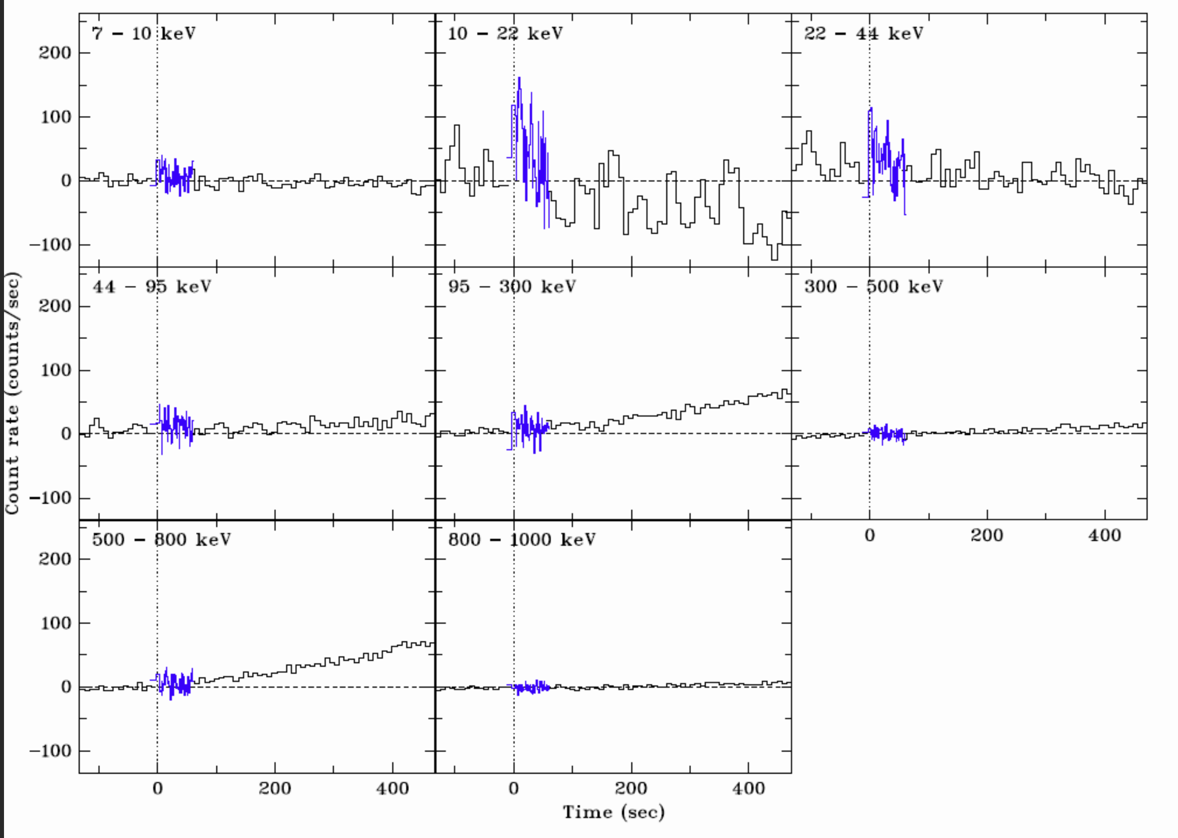
Galactic Source Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Galactic Sources		No			N/A	



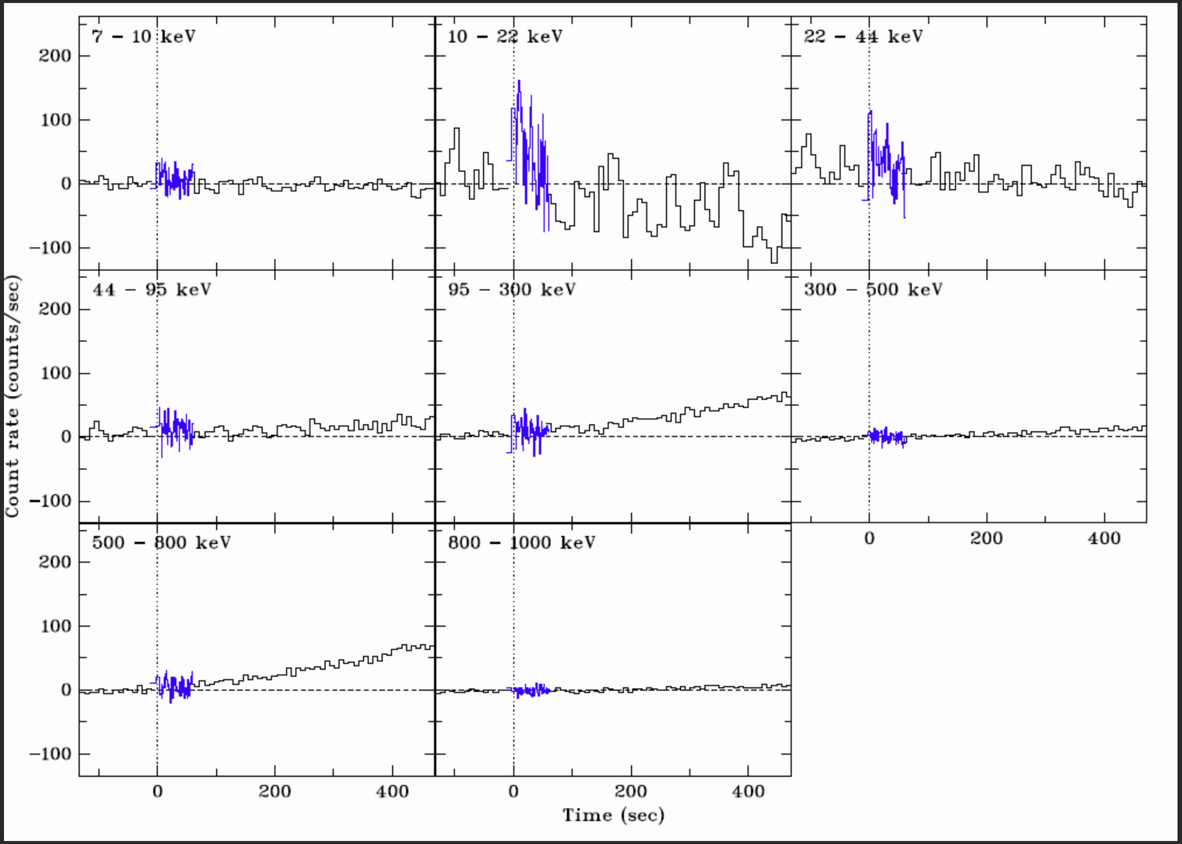
Galactic Source Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Galactic Sources		No	No		**N/A**	



Galactic Source Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Galactic Sources	?	No	No	?	N/A	No

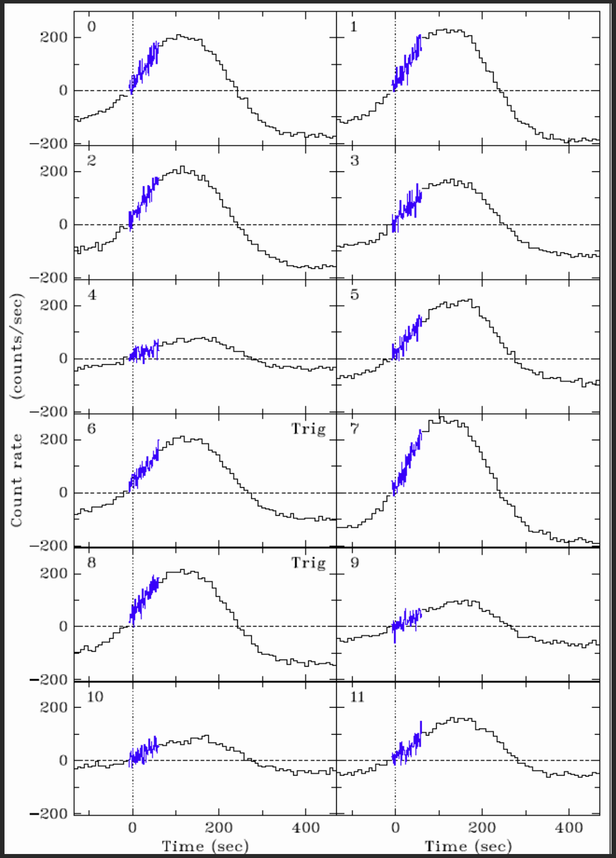


Earth Magnetospheric Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Magneto-spheric						

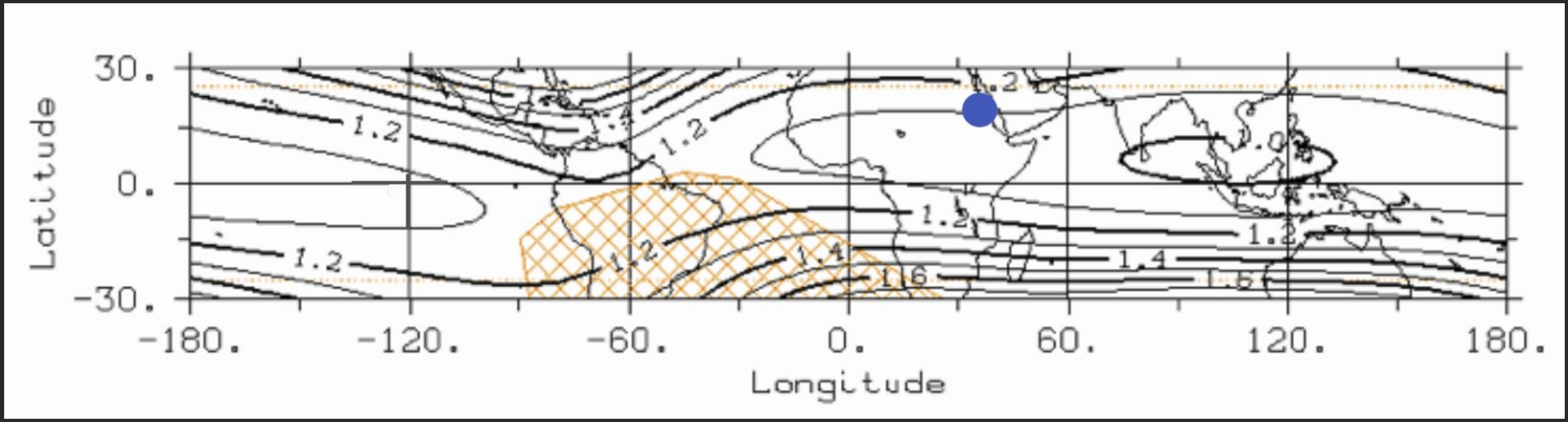
Earth Magnetospheric Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Magneto-spheric	No			No		



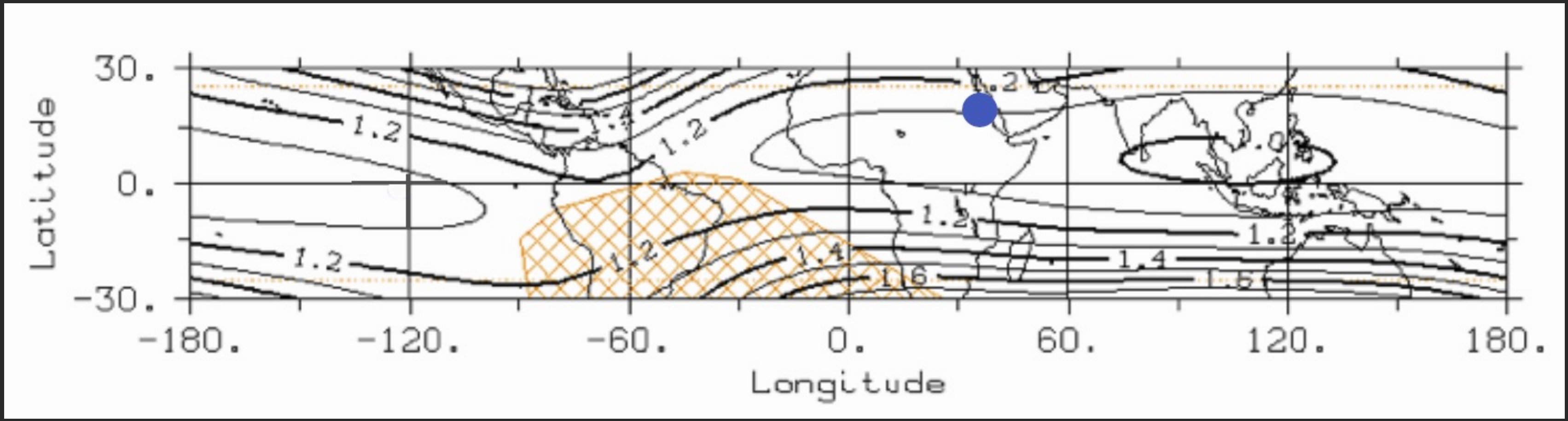
Earth Magnetospheric Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Magneto-spheric	No			No	No	



Earth Magnetospheric Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Magneto-spheric	No	?	?	No	No	No

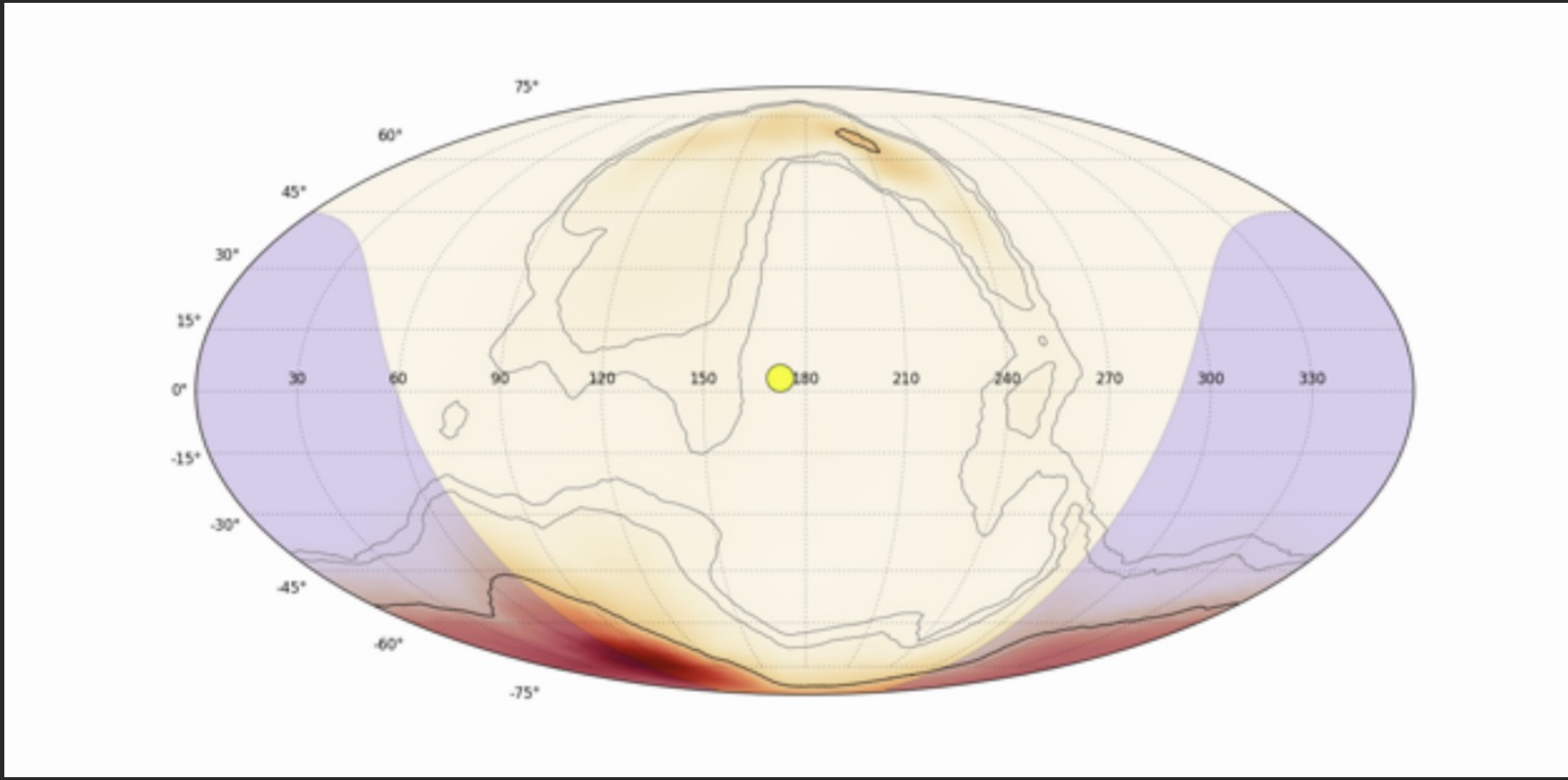


Solar Activity Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Solar Activity					N/A	

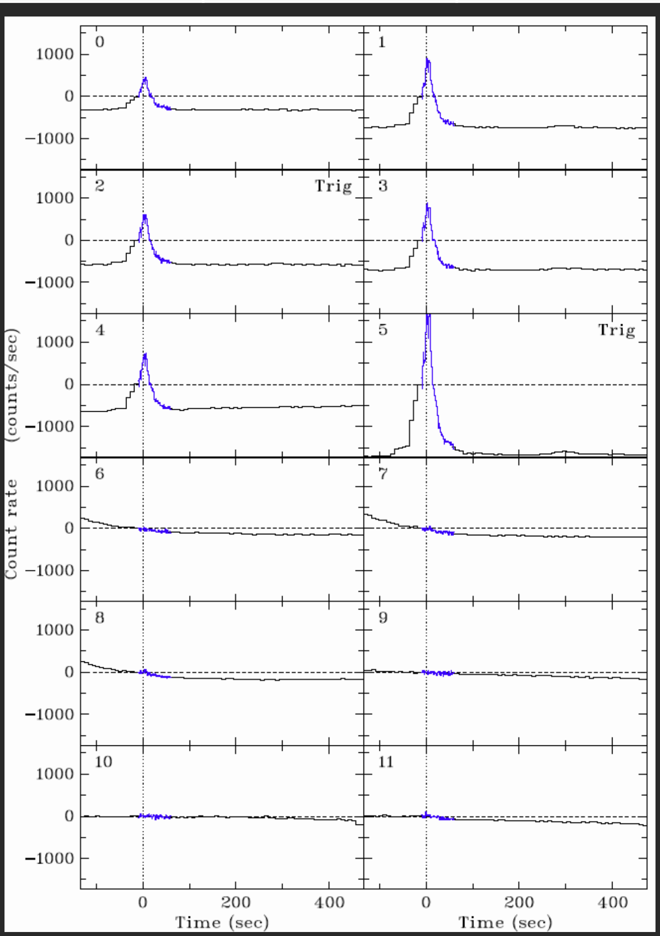
Solar Activity Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Solar Activity		No			N/A	



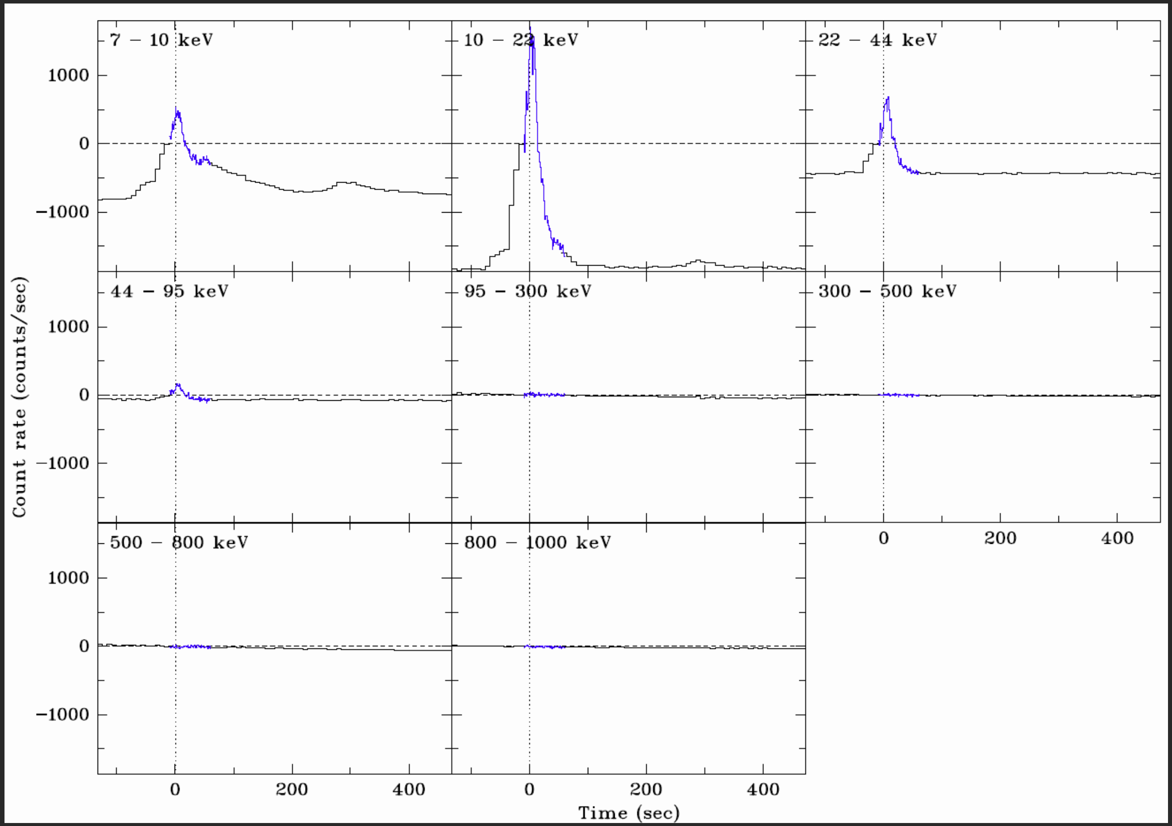
Solar Activity Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Solar Activity		No		No	N/A	



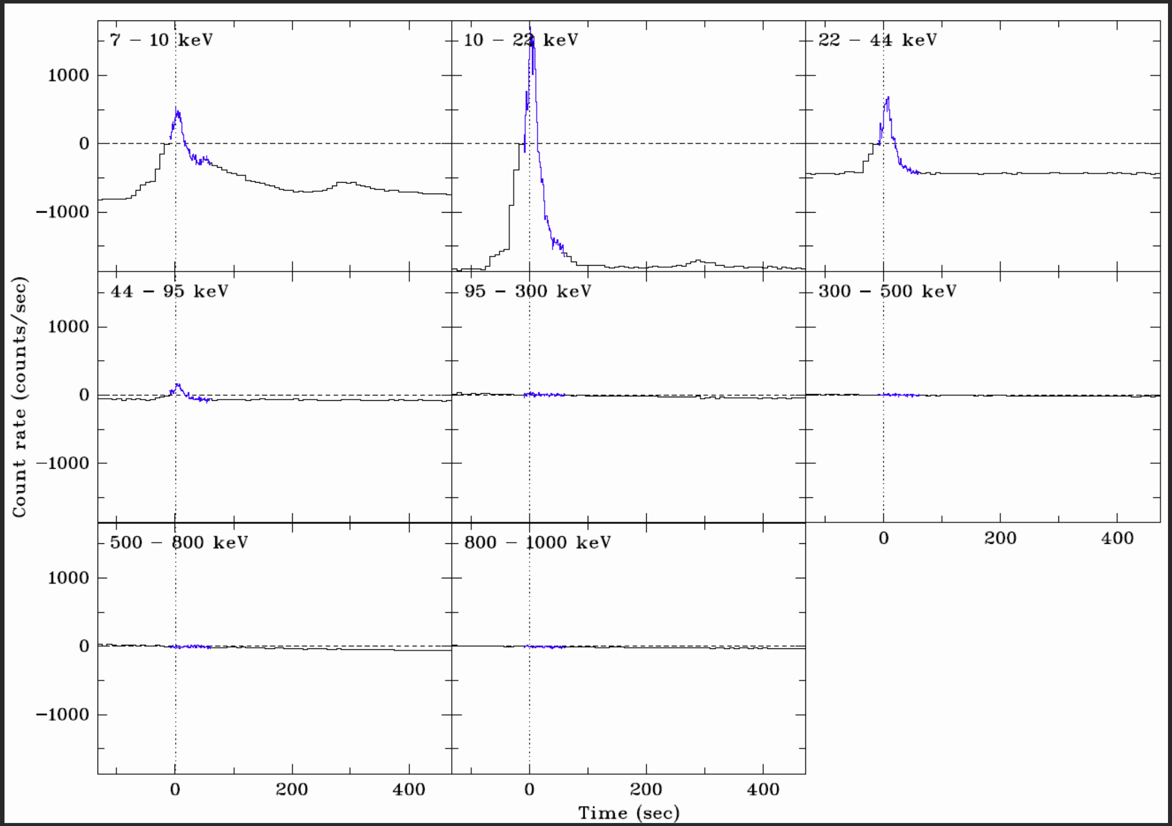
Solar Activity Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Solar Activity		No	No	No	N/A	



Solar Activity Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Solar Activity	?	No	No	No	N/A	No



Some New Origin?

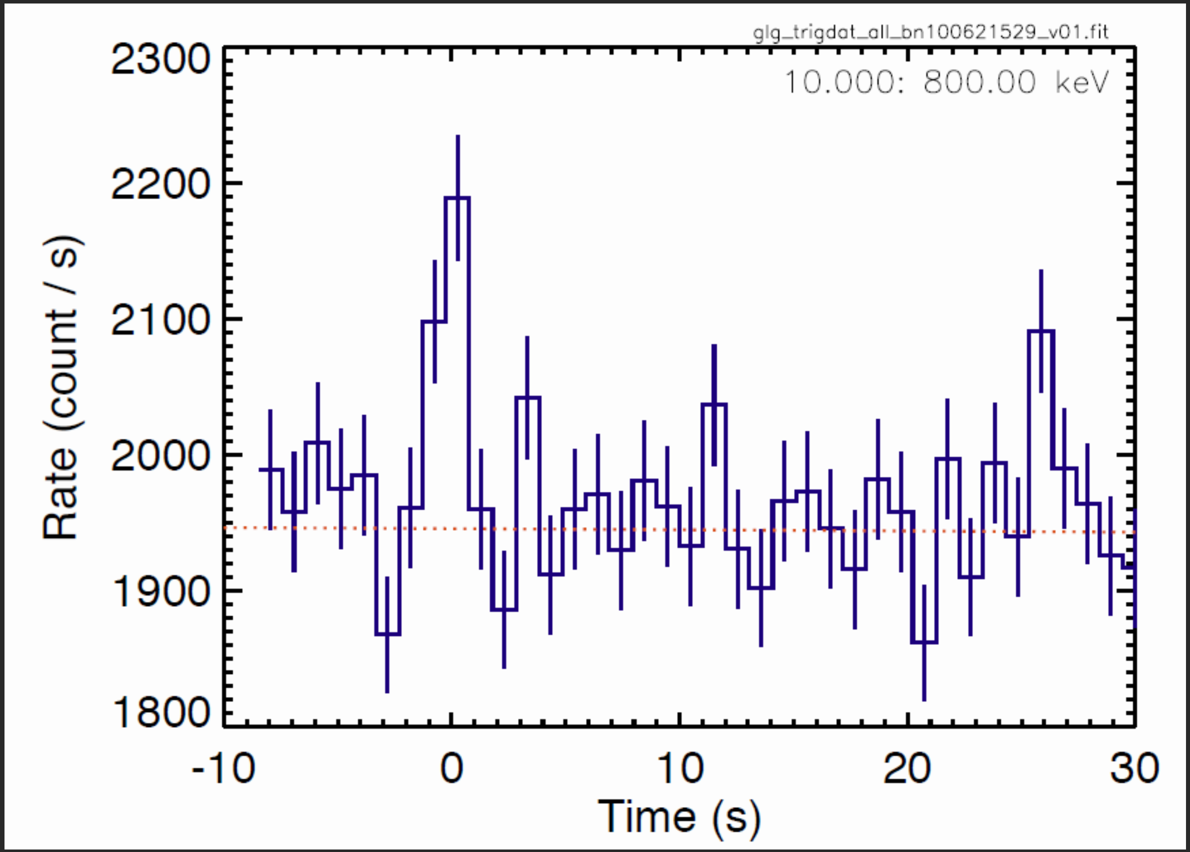
	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Something New	?	?	?	?	?	?

Short GRB Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Short GRB					N/A	

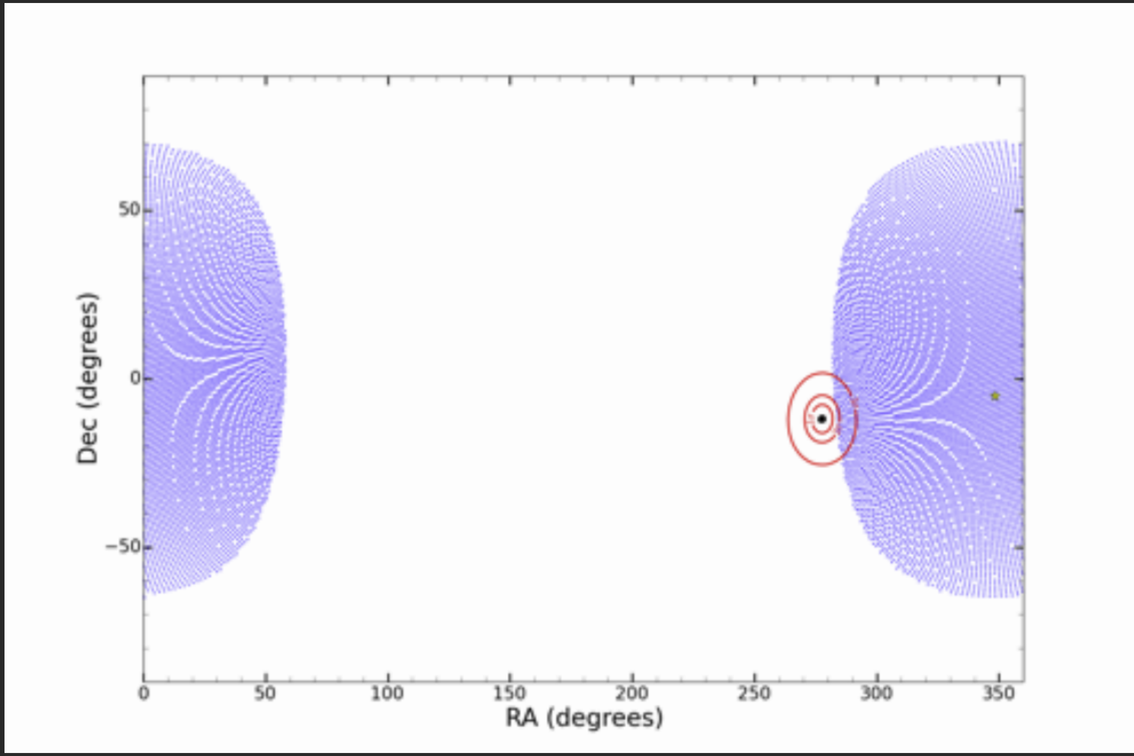
Short GRB Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Short GRB	Yes			Yes	N/A	



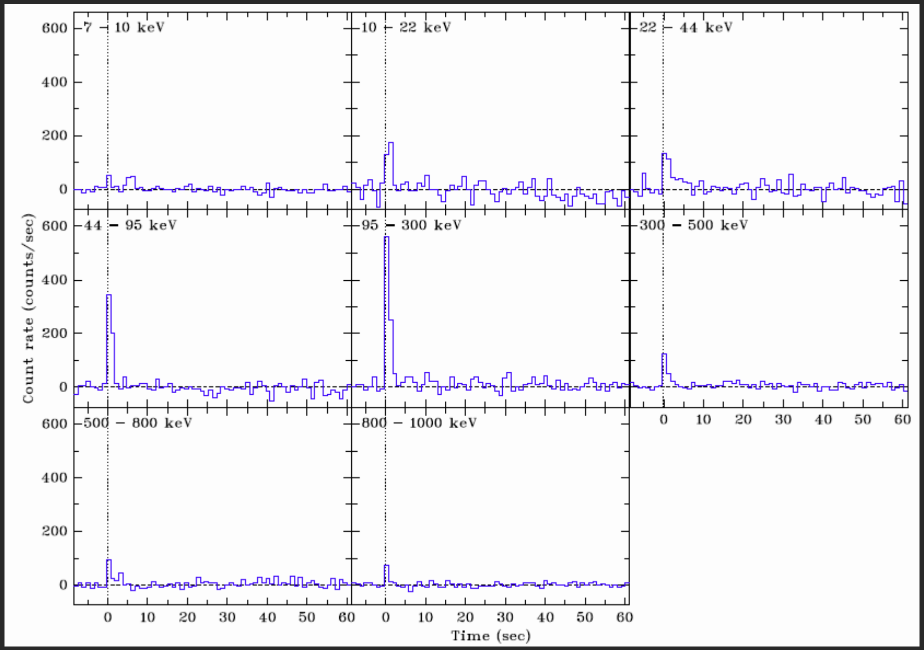
Short GRB Origin?

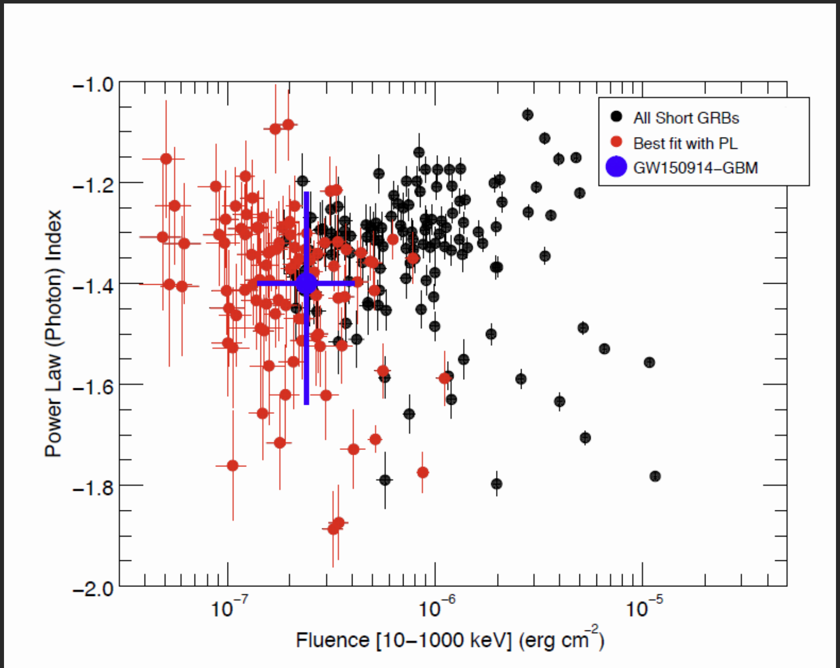
	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Short GRB	Yes	Yes		Yes	N/A	



Short GRB Origin?

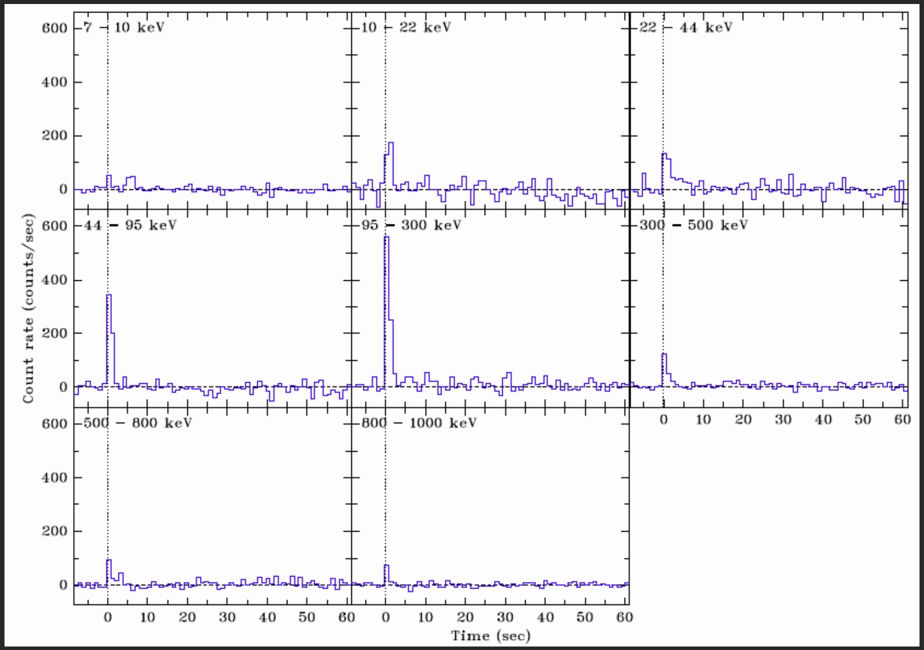
	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Short GRB	Yes	Yes	Yes	Yes	N/A	

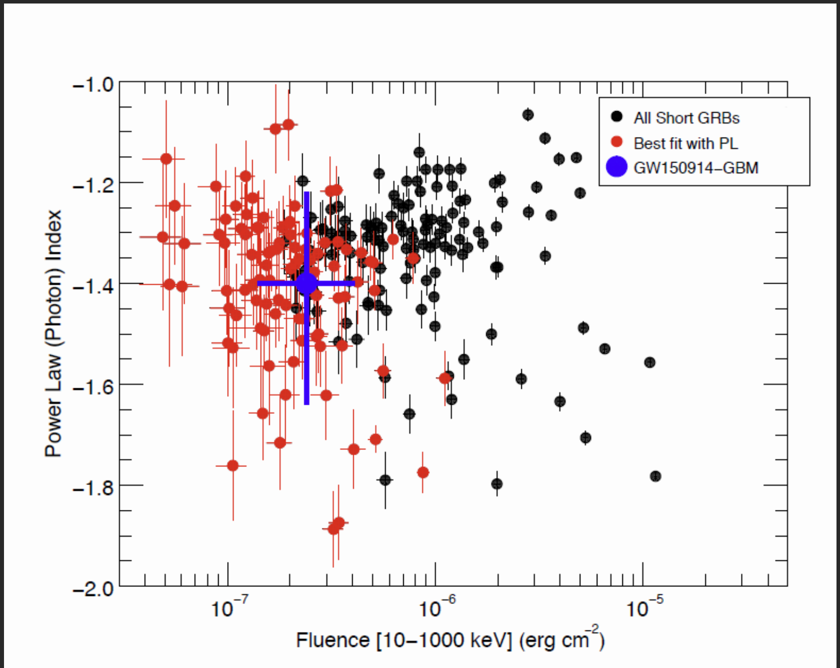




Short GRB Origin?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Short GRB	Yes	Yes	Yes	Yes	N/A	Yes





What Could It Be?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs/TEBs)	No	No	?	No	No	No
Galactic Sources	?	No	No	?	N/A	No
Magneto spheric	No	?	?	No	No	No
Solar Activity	?	No	No	No	N/A	No
Something New	?	?	?	?	?	Maybe? Unlikely
Short GRB	Yes	Yes	Yes	Yes	N/A	Yes

What Could It Be?

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs/TEBs)	No	No	?	No	No	No
Galactic Sources	?	No	No	?	N/A	No
Magneto spheric	No	?	?	No	No	No
Solar Activity	?	No	No	No	N/A	No
Something New	?	?	?	?	?	Maybe? Unlikely
Short GRB	Yes	Yes	Yes	Yes	N/A	Yes

The most likely explanation is a short GRB …

…but is it related to GW150914?

- False Alarm Probability Calculation
  - False Alarm Rate (FAR) = 27 hard events in 218821.1 s of GBM live time, factor of 3 for spectra searched, 90% confidence

FAR

Delay between GW and EM signal

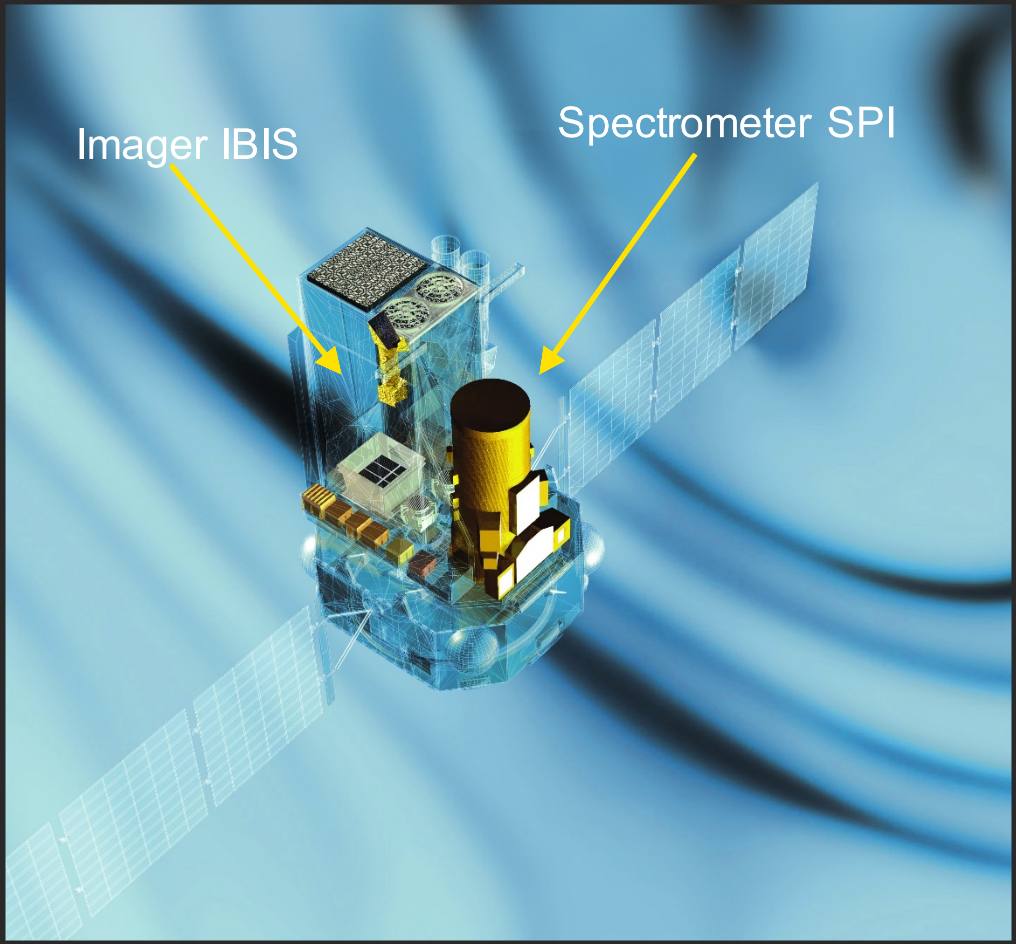
$$P = 2 \times (4.79e\text{-}4) \times (0.4\ s) \times (1 + \ln(30\ s / 0.256\ s)) = 0.0022$$

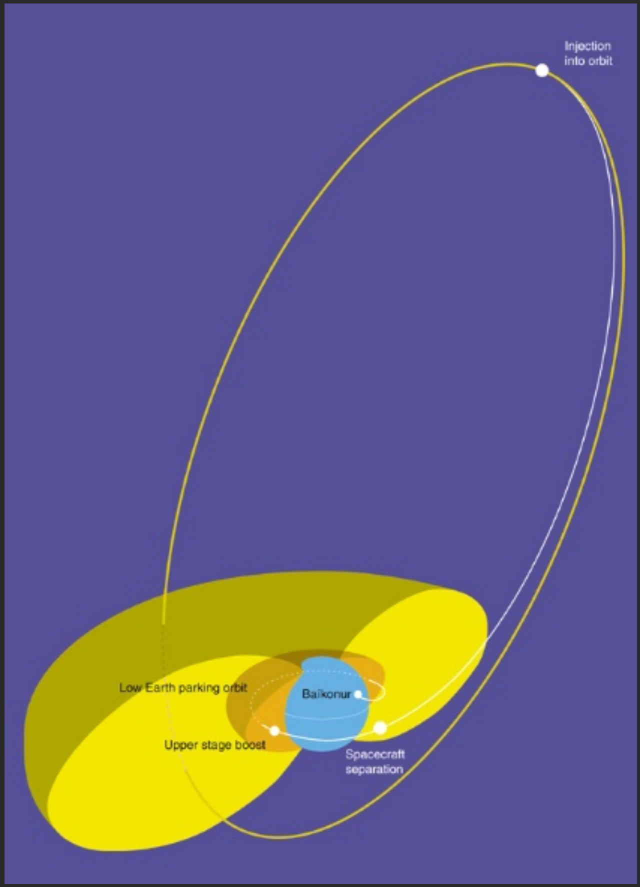
Factor for direction of delay

Effective trials factor for bins/durations searched

- For details see https://dcc.ligo.org/public/0122/T1500534/002/coincsig.pdf

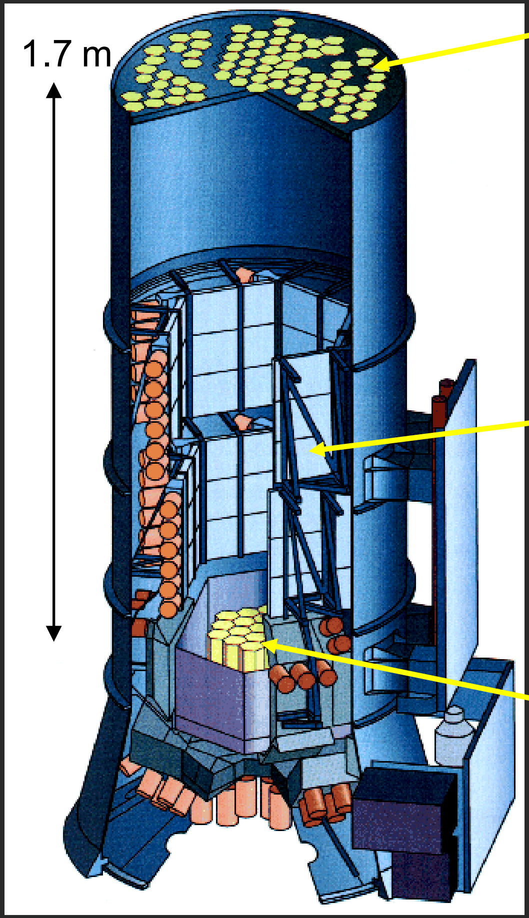
INTEGRAL spacecraft & scientific payload





- Launched 17. Oktober 2002

Spectrometer SPI

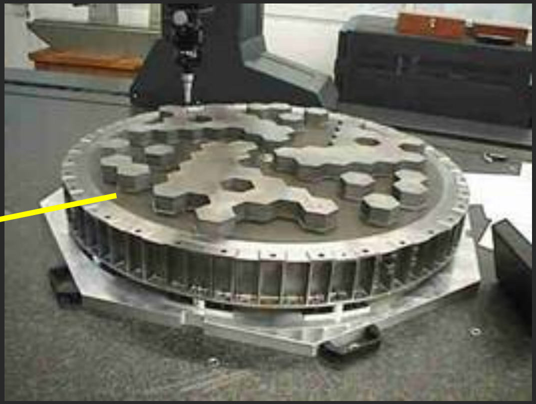


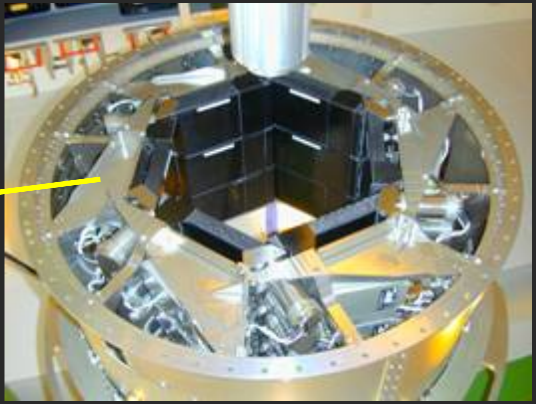
Coded Mask

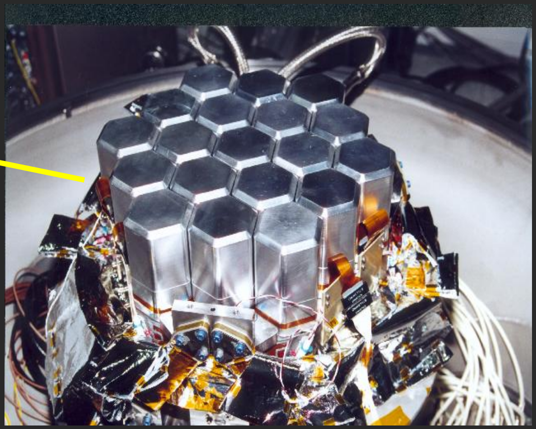
Veto Shield

19 Germanium

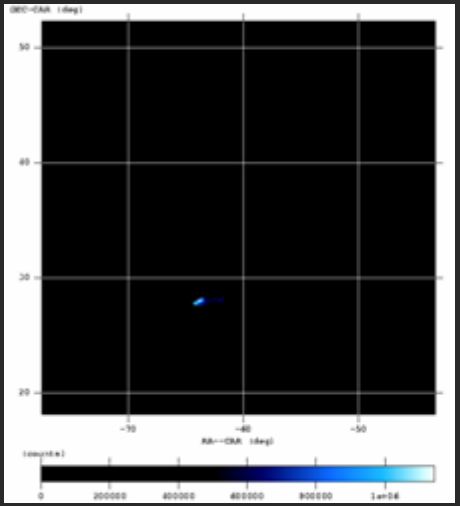
Detectors





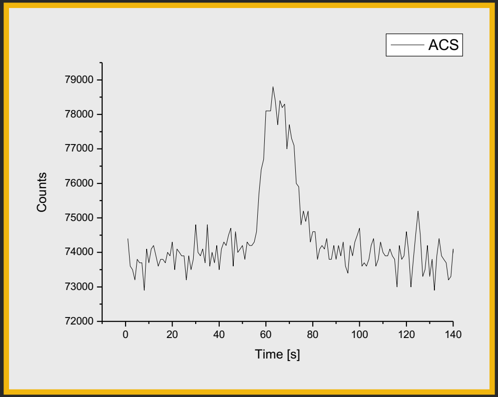


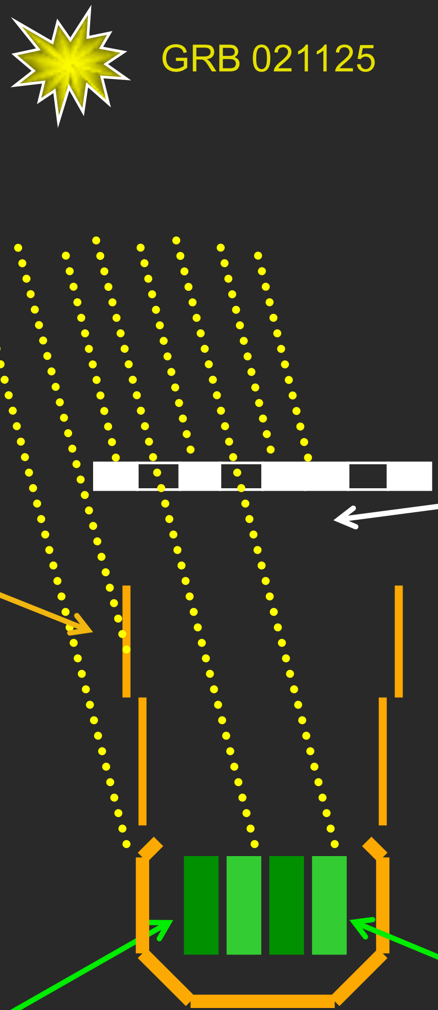
GRB021125 – detected by SPI



GRB 021125

GRB seen by ACS

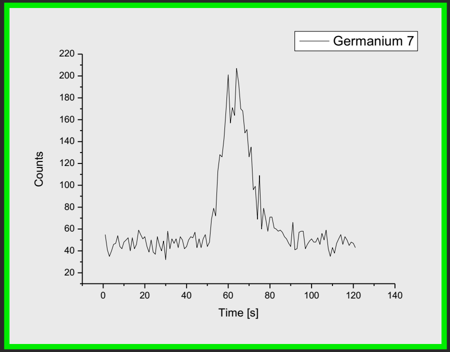




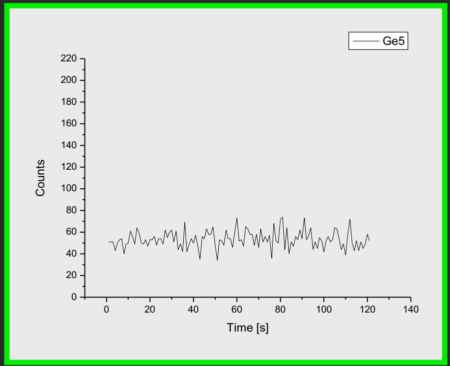
"Shadows"

from coded mask

GRB seen by a Germanium detector

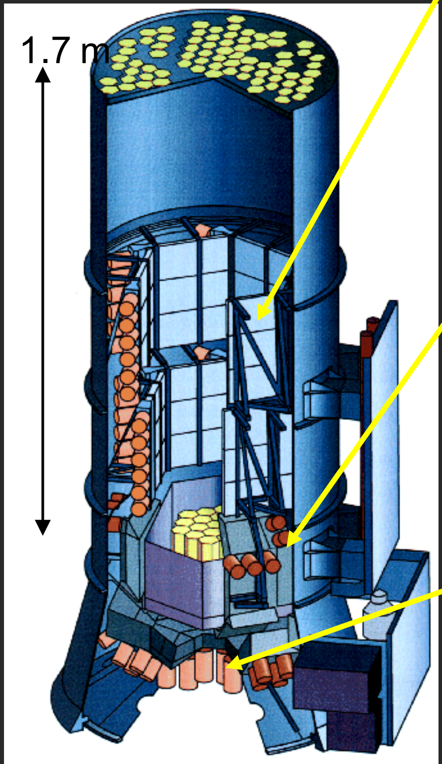


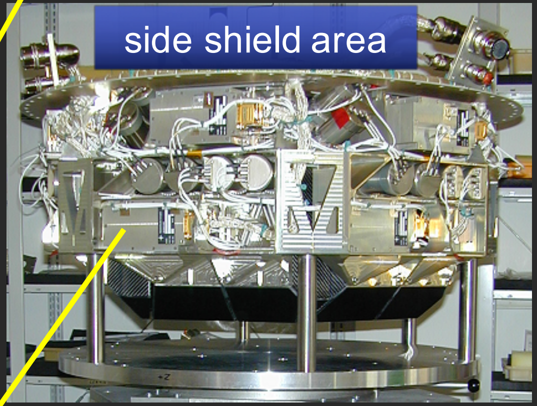
Shadowed detector !

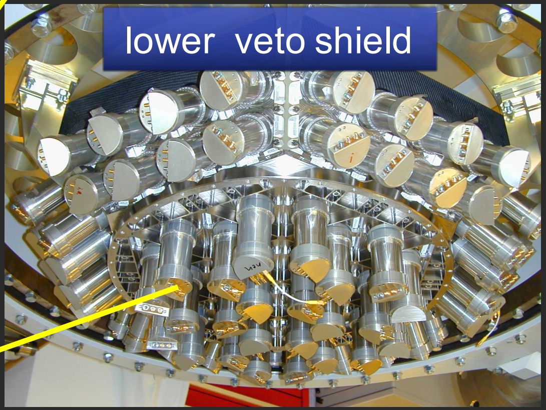


Anticoincidence shield ACS

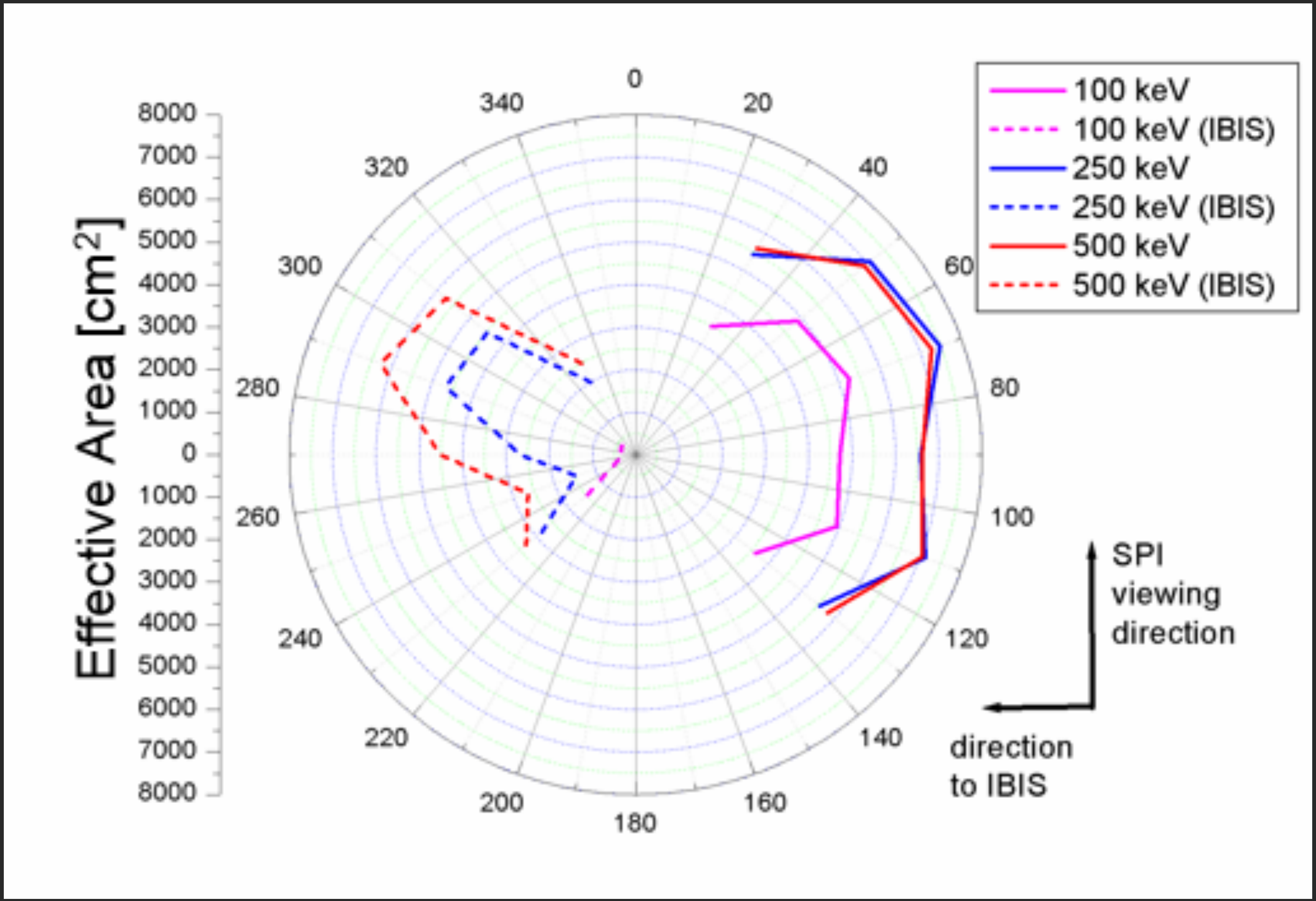
- German contribution to SPI
  - DLR: financial support (~20 M€)
  - MPE: scientific lead
  - Astrium, Jena Optronik: industrial contractors
- 91 BGO-crystals arranged in
  - 2 Collimator Rings UCR + LCR
  - Side-Shield Area SSA
  - Lower Veto Shield LVS
  - ⇨ **512 kg of BGO !**
- 181 PMTs
- 91 FEEs
- VCU (main/redundant)
  - ⇨ **Generating 1 ORed Veto**
- No spectral information







SPI-ACS Effective Area



ACS threshold function

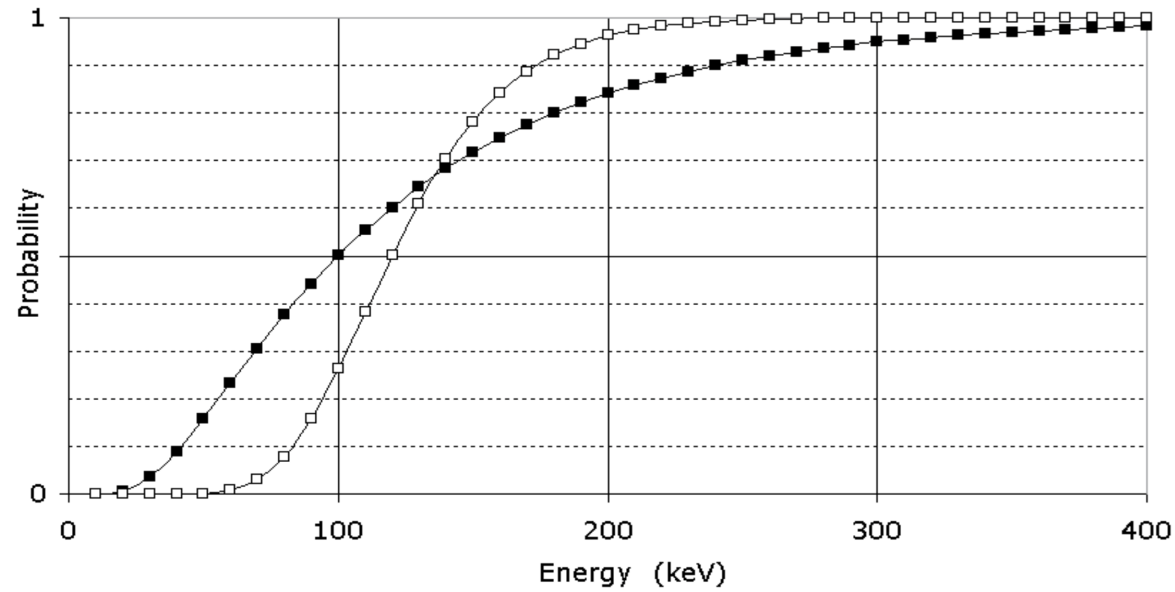


Fig. 10. For PMT_1(solid), $E_{th} = 100$ keV and $a = \sqrt{50}$, for PMT_2(open), 120 keV and $\sqrt{10}$. These curves illustrate the large differences between ACS crystals and PMTs combinations.

Common ACS threshold:

$\sim 75^{+75}_{-25}$ keV

$$s(E, E_{th}) = \frac{1}{\sigma(E) \times \sqrt{2\pi}} \times \int_{E_{th}}^{+\infty} e^{-\frac{(E' - E)^2}{2\sigma^2(E)}} \, dE'$$

$$\sigma(E) = a \times \sqrt{E}$$

GBM ↔ SPI/ACS

- SPI-ACS is the anti-coincidence shield for the SPI instrument
  - Observes (almost) the entire sky
  - No spatial resolution
  - No energy resolution (everything >75 keV)
  - Not intended to be a science instrument
- SPI-ACS non-detection is **not constraining** for the GBM event
  - SPI-ACS and GBM look at the sky in different energy range
  - GBM cannot constrain the spectrum of this event very well
  - Extrapolating an unknown spectrum from GBM into what ACS should have seen is a very difficult problem
  - Even the uncertainties quoted for both instruments are statistical only
- There is a significant fraction of GBM-triggered short GRBs not seen in the SPI-ACS
  - Not clear why — spectral uncertainties, poorly-modeled sensitivity?
  - GBM and SPI-ACS are working together to better understand the systematics between the two instruments !

Summary

- Untriggered sub-threshold signal
  - 0.4 s after LIGO GW trigger
  - Consistent with a low-fluence short GRB coming from behind *Fermi*
  - Summed ligtcurve SNR ~6 sigma
  - poorly localized, but consistent with LIGO localization
  - 0.2% probability of statistical fluctuation
- GBM instrument best suited for EM counterpart search of GW events